2010-09

Evaluating Atlantic tropical cyclone track error distributions for use in probabilistic forecasts of wind distribution

Neese, Jay M.

Monterey, California. Naval Postgraduate School

NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

THESIS

EVALUATING ATLANTIC TROPICAL CYCLONE TRACK ERROR DISTRIBUTIONS FOR USE IN PROBABILISTIC FORECASTS OF WIND DISTRIBUTION

by

Jay M. Neese

September 2010

Thesis Advisor:	Patrick A. Harr
Second Reader:	Russell L. Elsberry

THIS PAGE INTENTIONALLY LEFT BLANK

REPORT DOCUMENTATION PAGE			*Form Approved OMB No. 0704-0188*
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instruction, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188) Washington DC 20503.			
1. AGENCY USE ONLY *(Leave blank)*	**2. REPORT DATE** September 2010	**3. REPORT TYPE AND DATES COVERED** Master's Thesis	
4. TITLE AND SUBTITLE Evaluating Atlantic Tropical Cyclone Track Error Distributions for Use in Probabilistic Forecasts of Wind Distribution			**5. FUNDING NUMBERS**
6. AUTHOR(S) Jay M. Neese			
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Postgraduate School Monterey, CA 93943-5000			**8. PERFORMING ORGANIZATION REPORT NUMBER**
9. SPONSORING /MONITORING AGENCY NAME(S) AND ADDRESS(ES) N/A			**10. SPONSORING/MONITORING AGENCY REPORT NUMBER**
11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government. IRB Protocol number ______N/A___________.			
12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution is unlimited			**12b. DISTRIBUTION CODE**
13. ABSTRACT (maximum 200 words) This thesis investigates whether the National Hurricane Center (NHC) operational product for producing probabilistic forecasts of tropical cyclone (TC) wind distributions could be further improved by examining the distributions of track errors it draws upon to calculate probabilities. The track spread/skill relationship for several global ensemble prediction system forecasts is examined as a condition for a description of a full probability distribution function. The 2007, 2008, and 2009 NHC official track forecasts are compared to the ensemble prediction system model along-, cross-, and forecast-track errors. Significant differences in statistical properties were then identified among the groups to determine whether conditioning based on geographic location was warranted. Examination of each regional distribution interval suggests that differences in distributions existed for along-track and cross-track errors. Because errors for ensemble mean and deterministic forecasts typically have larger mean errors and larger variance than official forecast errors, it is unlikely that independent error distributions based on these models would refine the PDFs used in the probabilistic model. However, this should be tested with a sensitivity analysis and verified with the probability swath. Overall, conditional formatting suggests that the NHC probability product may be improved if the Monte Carlo (MC) model would draw from refined distributions of track errors based on TC location.			
14. SUBJECT TERMS Tropical Cyclone Track Errors, Tropical Cyclone Winds, Probabilistic Forecast Confidence, National Hurricane Center			**15. NUMBER OF PAGES** 87
			16. PRICE CODE
17. SECURITY CLASSIFICATION OF REPORT Unclassified	**18. SECURITY CLASSIFICATION OF THIS PAGE** Unclassified	**19. SECURITY CLASSIFICATION OF ABSTRACT** Unclassified	**20. LIMITATION OF ABSTRACT** UU

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18

THIS PAGE INTENTIONALLY LEFT BLANK

Approved for public release; distribution is unlimited

EVALUATING ATLANTIC TROPICAL CYCLONE TRACK ERROR DISTRIBUTIONS FOR USE IN PROBABILISTIC FORECASTS OF WIND DISTRIBUTIONS

Jay M. Neese
Captain, United States Air Force
B.S., United States Air Force Academy, 2003

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN METEOROLOGY

from the

NAVAL POSTGRADUATE SCHOOL
September 2010

Author: Jay M. Neese

Approved by: Patrick A. Harr
Thesis Advisor

Russell L. Elsberry
Second Reader

Philip A. Durkee
Chairman, Department of Meteorology

THIS PAGE INTENTIONALLY LEFT BLANK

ABSTRACT

This thesis investigates whether the National Hurricane Center (NHC) operational product for producing probabilistic forecasts of tropical cyclone (TC) wind distributions could be further improved by examining the distributions of track errors it draws upon to calculate probabilities. The track spread/skill relationship for several global ensemble prediction system forecasts is examined as a condition for a description of a full probability distribution function. The 2007, 2008, and 2009 NHC official track forecasts are compared to the ensemble prediction system model along-, cross-, and forecast-track errors. Significant differences in statistical properties were then identified among the groups to determine whether conditioning based on geographic location was warranted. Examination of each regional distribution interval suggests that differences in distributions existed for along-track and cross-track errors. Because errors for ensemble mean and deterministic forecasts typically have larger mean errors and larger variance than official forecast errors, it is unlikely that independent error distributions based on these models would refine the PDFs used in the probabilistic model. However, this should be tested with a sensitivity analysis and verified with the probability swath. Overall, conditional formatting suggests that the NHC probability product may be improved if the Monte Carlo (MC) model would draw from refined distributions of track errors based on TC location.

THIS PAGE INTENTIONALLY LEFT BLANK

TABLE OF CONTENTS

THIS PAGE INTENTIONALLY LEFT BLANK

LIST OF FIGURES

THIS PAGE INTENTIONALLY LEFT BLANK

LIST OF TABLES

THIS PAGE INTENTIONALLY LEFT BLANK

LIST OF ACRONYMS AND ABBREVIATIONS

AFB	Air Force Base
ATCF	Automated Tropical Cyclone Forecast system
ATE	Along-Track Error
CISL	Computational and Information Systems Laboratory
CTL	Control
DET	Deterministic
DoD	Department of Defense
ECB	Eastern Caribbean
ECMWF	European Center for Medium-Range Weather Forecasts
ECS	East Coast
EMN	Ensemble Mean
EPS	Ensemble Prediction System
FTE	Forecast-Track Error
GFS	Global Forecasting System
GOM	Gulf of Mexico
JTWC	Joint Typhoon Warning Center
MC	Monte Carlo
MDR	Main Development Region
NAS	Naval Air Station
NCAR	National Center for Atmospheric Research
NCEP	National Centers for Environmental Prediction
NHC	National Hurricane Center
OFC	Official
SBA	Subtropical Atlantic
TC	Tropical Cyclone
TD	Tropical Depression
TS	Tropical Storm
THORPEX	The Observing System Research and Predictability Experiment
TIGGE	THORPEX Interactive Grand Global Ensemble

UCAR	University Corporation for Atmospheric Research
UKMET	United Kingdom Meteorological (weather forecast model/office)
VAB	Vehicle Assembly Building
WCB	Western Caribbean
WS	Weather Squadron
WPFP	Wind speed Probability Forecast Product
XTE	Cross-Track Error

ACKNOWLEDGMENTS

Thank you to my wife, Lisa, my parents, Cliff and Jackie Neese, and the rest of my family who have supported and encouraged me throughout this academic endeavor.

I would like to thank my advisor, Professor Pat Harr, for his guidance, leadership, and technical expertise, Mr. Bill Roeder of the 45^{th} Weather Squadron, Patrick AFB, FL, who provided the motivation behind conducting this research, Professor Russell Elsberry for his thorough help with editing, Bob Creasey for all things computer-related, and all of my other professors who provided valuable guidance, instruction, and background material.

Finally, to my friends and NPS classmates who allowed me to maintain a high quality of life, while also ensuring I successfully completed all academic obligations.

THIS PAGE INTENTIONALLY LEFT BLANK

I. INTRODUCTION

A. MOTIVATION

Tropical cyclones (TCs) routinely affect society, the economy, the environment, and military operations. Although coastal counties in the contiguous United States account for only 17 percent of the total landmass, over 50 percent of the population lives within this region (NOS 2010). Between 1960 and 2008, the population of the U.S. coastline increased by 84 percent compared to a 69 percent increase in population for the entire country over the same time period. The Gulf of Mexico region alone has increased in population by 150 percent from 1960 to 2008 (Wilson 2010). During the next several decades, these coastal regions are expected to exponentially increase in population, and with these new residents. comes an increase in vulnerability to severe weather induced by tropical cyclones.

During the 2007–2009 hurricane seasons alone, 18 TCs either made landfall or came close enough to the U.S. coastline to become an evacuation or resource protection concern. Hurricane Ike, which made landfall in Cuba and the southeast Texas coast in September 2008, was the third costliest to hit the U.S. and the most substantial in deaths and destruction since Hurricane Katrina in 2005. Fortunately, models handled this storm particularly well, with the accuracy of most official forecasts significantly better than average (NHC 2010k). However, improvements to TC forecast models could have reduced the amount of lives lost and property damaged during this storm and could so for storms in the future as well.

Figure 1. (a) Waves crash over the Galveston Seawall and the memorial for the 1900 Galveston Hurricane before the arrival of Ike, (b) House on fire on Galveston Island as storm surge waters rise in advance of Ike, (c) Devastation on the Bolivar Peninsula due to storm surge from Ike, (d) Before and after image of the Bolivar Peninsula depicting the effects of storm surge, (e) Debris, boats, and trailers on the southbound lanes of I-45 heading toward Galveston, and (f) Ships waiting to enter Galveston Bay after Hurricane Ike (From NHC 2010k).

Civilians along the U.S. coast are only part of the requirement for increasing tropical cyclone forecast accuracy. Military operations on land, sea, and air depend on accurate forecasts and adequate lead times to protect resources and ensure mission completion. A large number of military installations are along the Gulf Coast and Atlantic states from Naval Air Station (NAS) Kingsville, TX to NAS Key West, FL, to Portsmouth Naval Shipyard, ME.

One installation that is highly vulnerable to TCs is Patrick Air Force Base, FL, where the 45th Weather Squadron (WS) is in charge of forecasting for launches at Kennedy Space Center and the Eastern Range at Cape Canaveral. Billions of dollars in equipment, facilities, and flight hardware, as well as the personnel and families who support the mission at these two sites, are vulnerable to the threats of TCs. Resource protection decisions made by NASA and Air

Force senior leadership rely on critical guidance from the 45th WS on track, storm size, and intensity based on NHC forecasts.

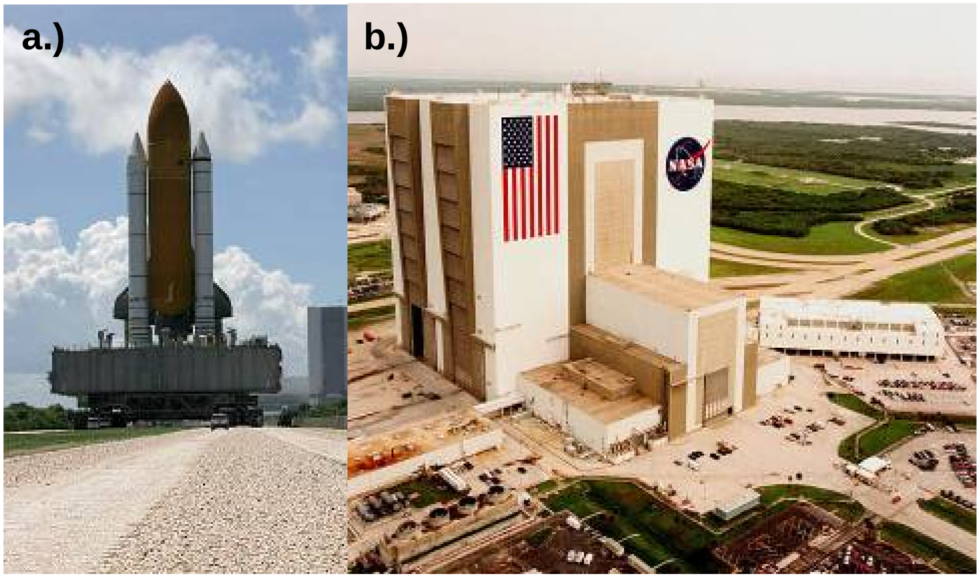


Figure 2. Space shuttle (a) in process of rollback to Vehicle Assembly Building pictured in panel (b) (From Astroprof 2010).

Particularly sensitive to hazardous weather associated with TCs is the space shuttle, which requires a rollback to the Vehicle Assembly Building (VAB) from the launch pad prior to the onset of sustained 40-knot winds. Planners require at least 48 hours to make a decision on initiating a rollback due to the time-consuming process of halting launch operations and transporting the shuttle back to safety (Winters 2006). Forecasters at the 45th Weather Squadron rely on probabilistic forecasts to aid planners in making costly decisions such as a rollback. An overly cautious forecast resulting in a false alarm could cost hundreds of thousands of dollars and delayed scheduling of launches while a missed forecast could result in billions in dollars of damage to equipment or harm to personnel (Hauke 2006).

B. OBJECTIVE

Improving tropical cyclone track and intensity forecasts has long been the focus of the National Hurricane Center (NHC) and other agencies. In the 1980s, the National Weather Service (NWS) issued watch/warning graphical maps that included a white cone indicating the area where a TC was expected to verify 90% of the time. Improvements to this procedure by the NHC included strike probability forecasts in text format, which indicated the percentage of time a TC was expected to pass within 75 n mi to the right or 50 n mi to the left of a given point. A recent improvement is the use of a Monte Carlo (MC) model (DeMaria et al. 2009a) to calculate uncertainties in track, intensity, and wind radii. Hauke (2006) re-examined the track error distributions the MC model draws from by determining conditional distributions based on forecast confidence. An improved forecast ability resulted from this modification of the NHC operational wind probability program (DeMaria et al. 2009b).

The objective of this thesis is to increase tropical cyclone wind distribution forecast accuracy to protect lives and resources of both military and civilian entities. For this thesis, the following hypothesis will be investigated:

> The refinement of current distributions of forecast track errors based on conditions derived from a specific parameter such as location would improve NHC and JTWC tropical cyclone probabilistic wind distribution forecasts.

This hypothesis has particular relevance to the forecast support generated by the 45th WS, but civilian and military entities worldwide can aid from improvements to TC track forecasts and accurate wind distributions in the warnings.

This thesis will attempt to further improve TC forecasts by examining the distributions of track errors the NHC MC model draws upon to calculate probabilities. If it is possible to use different distributions for different situations, the value of the probabilistic output may be increased. Results of this particular study could lead to a reduction of the massive costs of overly cautious evacuations when forecast confidence is high, or even save lives by expanding the evacuation zone when forecast confidence is low.

Background material regarding important concepts related to this thesis is provided in Chapter II. The methodology used for this study is described in Chapter III. The results of the study are presented in Chapter IV, and the conclusions and future recommendations are given in Chapter V.

THIS PAGE INTENTIONALLY LEFT BLANK

II. BACKGROUND

A. NATIONAL WEATHER SERVICE PROBABILISTIC TROPICAL CYCLONE FORECASTS

The TC forecast cone product (Figure 3) developed over a quarter-century ago depicts the NHC's official track (solid black line for days 1–3 and dashed black line for days 45) with a shaded area (white for days 1–3 and stippled white for days 4–5) on either side indicating an approximate 67% probability of where the TC will likely go based on a sampling of track errors from the past five years (NHC 2010n). The forecast cone gives the general public a basic picture of where a TC is likely to go along with current watches and warnings along coastlines. This product was periodically updated with new track error statistics from its inception in 1983 until 2005, but relatively few changes have occurred in the product since then (DeMaria et al. 2009a).

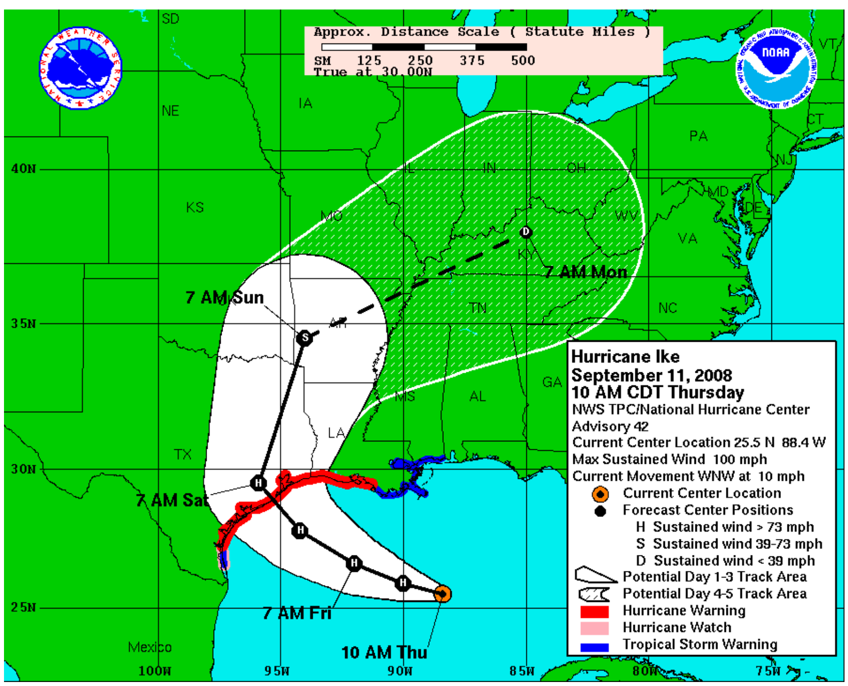


Figure 3. Hurricane Ike 5-day Watch/Warning/Forecast for 11 September 2008 (From NHC 2010g). The symbols are explained in the lower-right box, and an approximate distance scale for the cone is given at the top.

Since the beginning of the 2006 Atlantic and eastern North Pacific hurricane seasons, the NHC has been using tropical cyclone wind speed probability text and graphical products (NHC 2010o). Whereas previous forecasts focused more on single-track guidance, the goal of these new products has been to paint a more realistic picture of the actual weather that is forecast to occur at any given location. This probabilistic versus deterministic approach to forecasting allows decision-makers to better plan for the timing of weather events or for the likelihood that they will even occur at all (Wilks 2006).

Storm-specific text products contain two sections as shown in Figures 4 and 5. The Maximum Wind Speed (Intensity) Probability Table contains probabilities for maximum wind speeds at standard forecast hours for various intensity stages and for the five categories on the Saffir-Simpson Hurricane Scale (NHC 2010l).

```
ZCZC MIAPWSAT4 ALL
TTAA00 KNHC DDHHMM
HURRICANE IKE WIND SPEED PROBABILITIES NUMBER  42
NWS TPC/NATIONAL HURRICANE CENTER MIAMI FL   AL092008
1500 UTC THU SEP 11 2008

AT 1500Z THE CENTER OF HURRICANE IKE WAS LOCATED NEAR LATITUDE 25.5
NORTH...LONGITUDE 88.4 WEST WITH MAXIMUM SUSTAINED WINDS NEAR 85 KTS
...100 MPH...160 KM/HR.

Z INDICATES COORDINATED UNIVERSAL TIME (GREENWICH)
   ATLANTIC STANDARD TIME (AST)...SUBTRACT 4 HOURS FROM Z TIME
   EASTERN  DAYLIGHT TIME (EDT)...SUBTRACT 4 HOURS FROM Z TIME
   CENTRAL  DAYLIGHT TIME (CDT)...SUBTRACT 5 HOURS FROM Z TIME


I.  MAXIMUM WIND SPEED (INTENSITY) PROBABILITY TABLE

CHANCES THAT THE MAXIMUM SUSTAINED (1-MINUTE AVERAGE) WIND SPEED OF
THE TROPICAL CYCLONE WILL BE WITHIN ANY OF THE FOLLOWING CATEGORIES
AT EACH OFFICIAL FORECAST TIME DURING THE NEXT 5 DAYS.
PROBABILITIES ARE GIVEN IN PERCENT.  X INDICATES PROBABILITIES LESS
THAN 1 PERCENT.


      - - - MAXIMUM WIND SPEED (INTENSITY) PROBABILITIES - - -

VALID TIME   00Z FRI 12Z FRI 00Z SAT 12Z SAT 12Z SUN 12Z MON 12Z TUE
FORECAST HOUR   12      24      36      48      72      96     120
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
DISSIPATED       X       X       X       X      51      75      NA
TROP DEPRESSION  X       X       X       1      31      18      NA
TROPICAL STORM   1       2       6      16      14       5      NA
HURRICANE       99      99      94      83       4       2      NA
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
HUR CAT 1       23      21      14      27       1       X      NA
HUR CAT 2       61      42      25      25       1       X      NA
HUR CAT 3       16      32      41      23       1       1      NA
HUR CAT 4        X       3      11       8       1       X      NA
HUR CAT 5        X       X       1       X       X       X      NA
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
FCST MAX WIND   90KT    95KT   105KT   100KT    35KT    25KT    NA
```

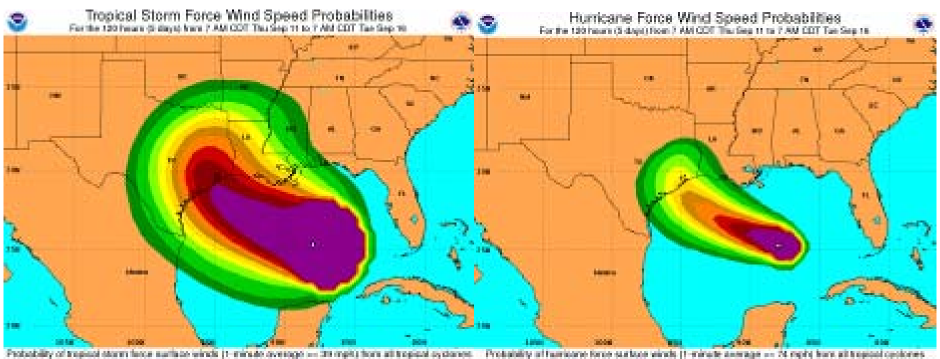
Figure 4. Maximum wind speed (intensity) probability table for Hurricane Ike Advisory #42 (From NHC 2010m).

The wind speed probability table for specific locations in section II (Figure 5) contains wind speed probabilities for selected coastal and inland cities along with each forecast issued by the NHC. Each wind speed probability text product provides probabilities for wind speeds of at least 34 kt (39 mph, tropical storm force, 50 kt (58 mph), or 64 kt (74 mph, hurricane force) at each listed location. Cumulative probabilities of occurrence and individual period probabilities are included in section II, e.g., the overall probability that the stated wind speed will occur at each location during the period between hour 0 and each listed forecast hour. Individual period probabilities of onset indicate the chances that the stated wind speed will start during each individual period at each location (NHC 2010l).

```
II. WIND SPEED PROBABILITY TABLE FOR SPECIFIC LOCATIONS

CHANCES OF SUSTAINED (1-MINUTE AVERAGE) WIND SPEEDS OF AT LEAST
   ...34 KT (39 MPH... 63 KPH)...
   ...50 KT (58 MPH... 93 KPH)...
   ...64 KT (74 MPH...119 KPH)...
FOR LOCATIONS AND TIME PERIODS DURING THE NEXT 5 DAYS

PROBABILITIES FOR LOCATIONS ARE GIVEN AS IP(CP) WHERE
    IP  IS THE PROBABILITY OF THE EVENT BEGINNING DURING
        AN INDIVIDUAL TIME PERIOD (INDIVIDUAL PROBABILITY)
   (CP) IS THE PROBABILITY OF THE EVENT OCCURRING BETWEEN
        12Z THU AND THE FORECAST HOUR (CUMULATIVE PROBABILITY)

PROBABILITIES ARE GIVEN IN PERCENT
X INDICATES PROBABILITIES LESS THAN 1 PERCENT
PROBABILITIES FOR 34 KT AND 50 KT ARE SHOWN AT A GIVEN LOCATION WHEN
THE 5-DAY CUMULATIVE PROBABILITY IS AT LEAST 3 PERCENT.
PROBABILITIES FOR 64 KT ARE SHOWN WHEN THE 5-DAY CUMULATIVE
PROBABILITY IS AT LEAST 1 PERCENT.


  - - - - WIND SPEED PROBABILITIES FOR SELECTED  LOCATIONS - - - -

               FROM    FROM    FROM    FROM    FROM    FROM    FROM
  TIME       12Z THU 00Z FRI 12Z FRI 00Z SAT 12Z SAT 12Z SUN 12Z MON
PERIODS         TO      TO      TO      TO      TO      TO      TO
             00Z FRI 12Z FRI 00Z SAT 12Z SAT 12Z SUN 12Z MON 12Z TUE

FORECAST HOUR    (12)    (24)    (36)    (48)    (72)    (96)   (120)
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
LOCATION       KT

GFMX 290N 850W 34  4   1( 5)   X( 5)   X( 5)   X( 5)   1( 6)   X( 6)

PENSACOLA FL   34  2   2( 4)   X( 4)   X( 4)   1( 5)   1( 6)   X( 6)

GFMX 290N 870W 34 14   5(19)   1(20)   X(20)   1(21)   X(21)   X(21)

MOBILE AL      34  3   4( 7)   2( 9)   1(10)   2(12)   X(12)   X(12)

GULFPORT MS    34  7   8(15)   4(19)   1(20)   2(22)   1(23)   X(23)
```

Figure 5. Section II of the wind speed probability table for specific locations for Hurricane Ike Advisory #42 (From NHC 2010m).

Graphical probability products (Figure 6) identify regions where wind speeds of at least 34, 50, or 64 kt are expected to occur during cumulative time periods from 0–120-h in 12-h increments. These products represent where tropical storm force winds of at least 34 kt (Figure 6a) and hurricane force winds of at least 64 kt (Figure 6b) are expected occur for Ike. Drawing from operational forecast center track and intensity error distributions from the past five years, this Wind speed Probability Forecast Product (WPFP) uses a Monte Carlo (MC) method to generate 1000 realizations, or tracks, relative to a given forecast track (DeMaria et al. 2009a).



a) b)

Figure 6. (a) Tropical storm force wind speed probabilities and (b) hurricane force wind speed probabilities for Ike (2008) (From NHC 2010h and 2010i).

These products take the focus off the expected center-line path of the eye of the storm and convey to users where winds of a certain magnitude may occur. Decision-makers can then make cost-benefit analysis decisions based on the probability of winds occurring at specific locations rather than relying on a single forecast cone representing one official forecast track.

B. RECENT TC TRACK AND WIND DISTRIBUTION FORECAST IMPROVEMENT STUDIES

Studies have been conducted on the performance, validity, and potential improvements of the NHC Wind Probability Forecast Products (WPFP) introduced in 2006. Hauke (2006) examined distributions of forecast track errors conditioned on forecast confidence to determine if significant differences exist in distribution characteristics. He used two predictors to define forecast confidence: the Goerss Predicted Consensus Error (GPCE, (Goerss 2000)) and the Global Forecast System (GFS) ensemble spread. The distributions of total-, along-, and cross-track errors from NHC official forecasts were defined for low, average, and high forecast confidence. Distributions of the GFS ensemble mean total-track errors were also defined for these three forecast confidence levels. Standard hypothesis testing methods were used to examine distribution characteristics. Using the GPCE values, Hauke (2006) found significant differences in nearly all track error distributions for each level of forecast confidence. The GFS ensemble spread did not provide a basis for statistically different distributions. Hauke (2006) concluded that these results suggest the NHC probability model would likely be improved if the MC model would draw from distributions of track errors based on the GPCE measures of forecast confidence.

Shafer (2009) performed an objective evaluation of the WPFP performance and interpretation of the product for operational application, e.g., discerning which forecast probabilities represent low/moderate/high risk for the various wind speed and forecast interval categories. Shafer (2009) focused on four hurricane seasons from 2004-2007 and included all storms approaching areas of interest centered on Cocoa Beach, FL, Charleston, SC, New Orleans, LA, and Corpus Christi, TX. Verification statistics were computed for each of the 21 forecast categories of the NHC probability product; three wind speed criteria (>= 34 kt, >= 50 kt, and >= 64 kt) and seven forecast time intervals (12, 24, 36, 48, 72, 96, and 120-hours). Verifications included use of reliability and sharpness diagrams, as well as additional statistics designed to quantitatively measure the product performance. Shafer (2009) concluded that the WPFC performed well and within the acceptable range of skill, with the skill of the forecast system decreasing as forecast time interval increased.

Splitt et al. (2009) revised and expanded the Shafer (2009) study and found the NHC product has a tendency to over forecast in some 34 kt cases but sometimes under forecasts for the 60 kt cases. Results from the 50 kt cases were mixed but also exhibited a tendency to underforecast during the later intervals.

Majumdar and Finocchio (2009) examined the ability of ensemble prediction systems to predict the probability that a tropical cyclone will fall within a certain area. Ensemble forecasts issued by the European Center for Medium-range Weather Forecasts (ECMWF) and the United Kingdom Meteorological Office (UKMET) of up to five days were evaluated for the 2008 Atlantic and western North Pacific seasons. The results demonstrated the potential for ensemble prediction systems to enhance probabilistic forecasts, and for the THORPEX Interactive Grand Global Ensemble (TIGGE) to be utilized by the operational and research communities.

DeMaria et al. (2009) evaluated performance of the MC probability model in the Atlantic and Pacific basins for the 2006–2007 seasons and concluded that the model is relatively unbiased, and the forecasts are skillful using a Brier skill score and a relative operating characteristic score. DeMaria et al. (2009) also determined that basin-wide error statistics are a current limitation to the model and noted that it is possible to estimate the error of a given track forecast based upon the spread of a consensus of track models and other information known at the time the official forecast is made (Goerss 2007).

Results of these studies during the past four years indicate the NHC WPFP is an effective and beneficial forecast tool and that consensus models could enhance the performance of these products. Furthermore, conditioning on certain parameters such as forecast spread (Hauke 2006) may also improve the WPFP. Continued confirmation of the contributions of these products to increased effectiveness means continued research to improve these products is both worthwhile and necessary.

III. METHODOLOGY

A. DATA

1. Data Source

The database for this study is from the 2007, 2008, and 2009 Atlantic hurricane seasons. With 40 named tropical storms and five unnamed tropical depressions, 1150 official forecasts were issued by the NHC during these three seasons. Considering there are seven time periods for each forecast (12, 24, 36, 48, 72, 96, and 120-h), the number of potential track forecast errors is 8050 for all three years. By combining results from all three seasons, it is expected that this was a large enough data set to test the hypothesis of this thesis.

While the 2005 season stands out as the most active on record, subsequent seasons have continued to influence civilian and military planners and operators. The 2007 season produced 14 named storms, which included six hurricanes, three of which reached major hurricane (Category 3 or higher) status (Figure 7). In addition, two tropical depressions also formed in the Atlantic. The numbers of hurricanes and major hurricanes were near the long-term averages for a season, but the number of named storms was slightly above average. For the first time since records began in 1851, two Category 5 hurricanes, Dean and Felix, made landfall during the 2007 season (NHC 2010a).

Dean made landfall as a Category 5 hurricane on the east coast of the Yucatan Peninsula and was responsible for about 40 deaths across the Caribbean, with the largest tolls in Mexico and Haiti. Felix made landfall as a Category 5 hurricane in Nicaragua and was responsible for 130 deaths in Nicaragua and Honduras as well as significant structural damage in Central America and the Caribbean Islands (NHC 2010a).

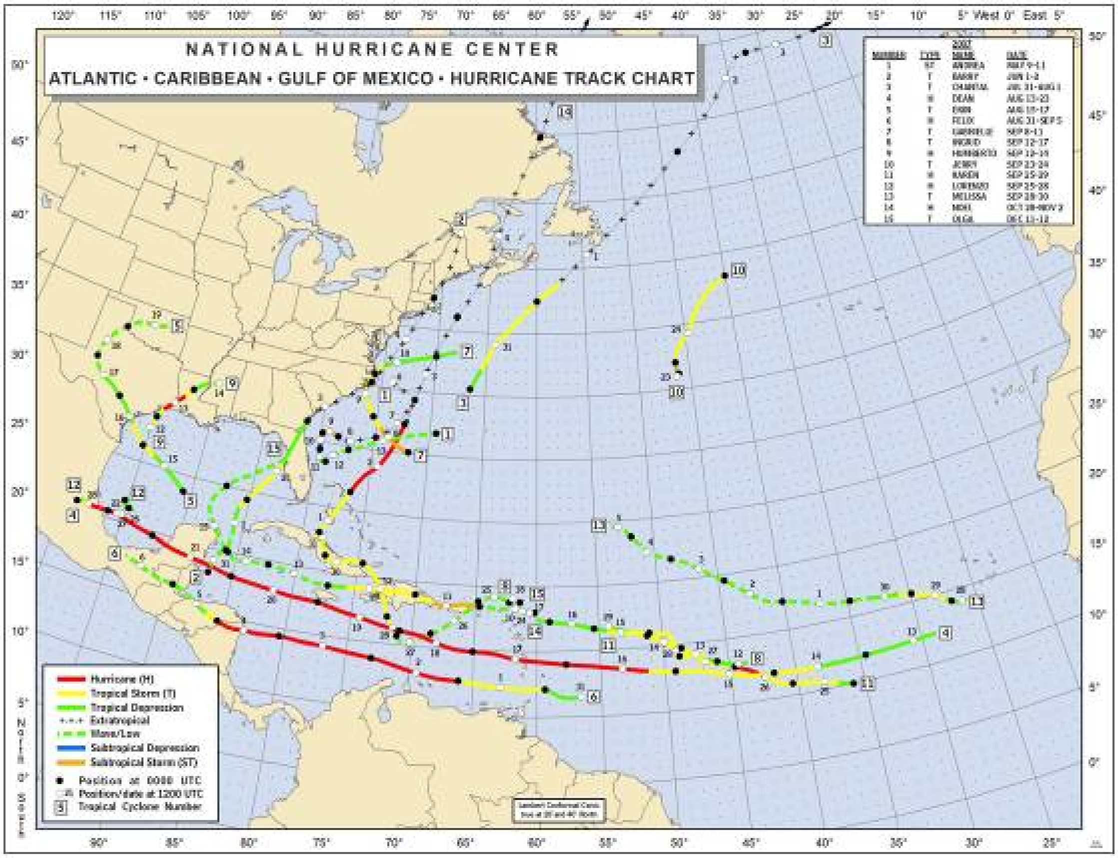


Figure 7. Tracks for the 2007 Atlantic hurricane season. The track symbols are explained in the lower-left box and the storm names are listed in the upper-right box. (From NHC 2010d)

The 2008 season (Figure 8) presented yet another challenge to forecasters, with an above-average 16 named storms in the Atlantic basin. Eight of these storms became hurricanes, and five strengthened into major hurricanes (NHC 2010b). Hurricanes Gustav, Hanna, and Ike were the most notable TCs in terms of deaths, with 112, 500, and 102 occurring, respectively. Major wind and storm surge damage occurred during Gustav's landfall in Cuba, and heavy rains in Haiti caused destructive mudslides. Strong winds, high storm surges, and heavy rains also caused an estimated 4.3 billion dollars damage in Louisiana (NHC 2010b). Hanna's very heavy rainfall in Haiti resulted in an estimated 500 fatalities, and minor wind and flood damage occurred in the Turks and Caicos Islands. In the U.S., damage was relatively minor, but occurred over a large area and totaled an estimated $160 million dollars (NHC 2010b). Hurricane Ike killed an estimated 74 people in Haiti and two people in the Dominican Republic with extensive wind and storm surge damage as it crossed the island of Cuba, where seven deaths were reported. Media reports indicated 19 direct TC-related deaths in Texas, Louisiana, and Arkansas. The remnants of Ike also caused wind damage and several dozen TC-indirect deaths across portions of the Mississippi and Ohio Valleys (NHC 2010b).

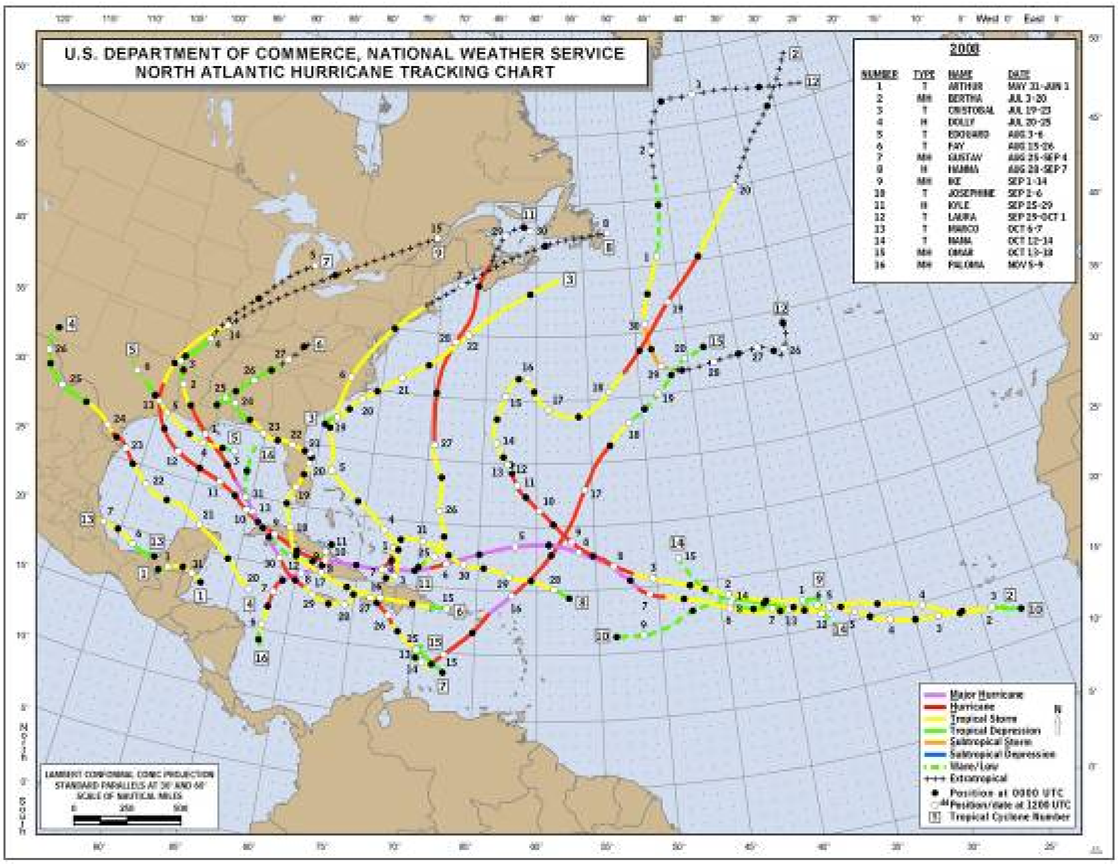


Figure 8. Tracks for the 2008 Atlantic hurricane season. The track symbols are explained in the lower-left box and the storm names are listed in the upper-right box. (From NHC 2010e)

While the 2009 season (Figure 9) had fewer storms, several different forecast scenarios occurred. The season contained nine named storms, three of which became hurricanes, and two of which became major hurricanes. There were also two tropical depressions that did not reach tropical storm strength (NHC 2010c).

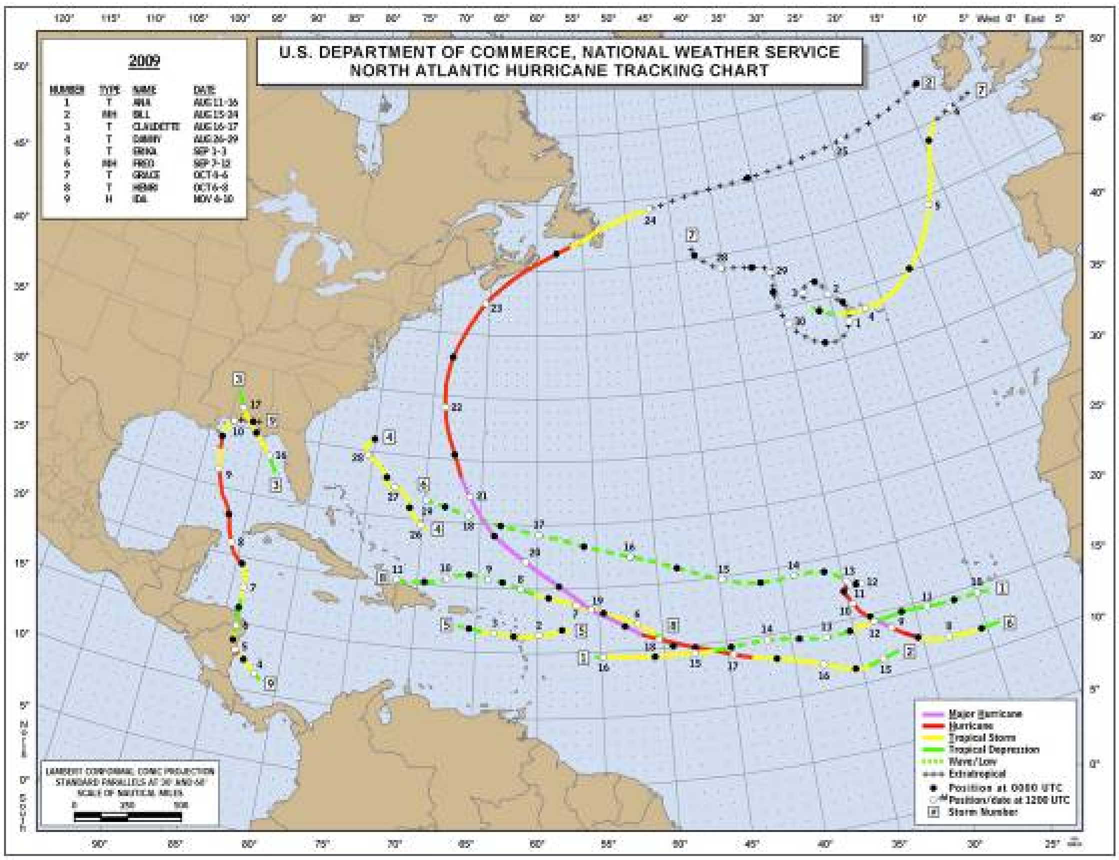


Figure 9. Tracks for the 2009 Atlantic hurricane season. The track symbols are explained in the lower-left box and the storm names are listed in the upper-right box. (From NHC 2010f)

The societal and physical impacts caused by each of these TCs during the 2007, 2008, and 2009 seasons underscore the importance of adequately preparing for the potentially overwhelming impacts of TCs. Perhaps the most significant tool for adequate preparation is early and accurate track forecasting with accurate wind distributions to warn people of the potential damage. This database from the 2007, 2008, and 2009 seasons will be used to test the basic hypothesis of the thesis.

2. Data Format

The data available from the NHC included every official forecast, a majority of the model forecasts, and all of the best-track positions of the TCs that occurred between 2007 and 2009. The A-Decks and B-Decks from the Automated Tropical Cyclone Forecast (ATCF) system as well as TIGGE (THORPEX (The Observing System Research and Predictability Experiment) Interactive Grand Global Ensemble) data were used in this thesis. The A-Decks are comprised of all the model and ensemble forecasts available to the NHC during the season along with their official (OFC) forecasts. Information included in the A-Decks are the storm number, model, forecast time and period, forecast intensity, and forecast position in latitude and longitude (Hauke 2006).

The B-Decks are the best-track positions of the Atlantic TCs in the 2007, 2008, and 2009 seasons. The best-track position is the verifying position of the TC after all the information has been evaluated in post-storm analysis. Included in these files are the storm number, date and time, intensity, and verifying location in latitude and longitude. Thus, the A-Decks can be used in conjunction with the B-Decks to calculate track forecast error (Hauke 2006).

Ensemble-based forecast tracks from three operational weather centers, United Kingdom Meteorological (UKMET), European Center for Medium-range Weather Forecasts (ECMWF), and National Centers for Environmental Prediction (NCEP), were obtained from the TIGGE data on the University Corporation for Atmospheric Research (UCAR) Computational and Information Systems Laboratory (CISL) Web site at http://dss.ucar.edu/datasets/ds330.3/MSS-file-list.html. These data are in a format similar to eXtensible Markup Language (XML) format, which is then labeled cyclone XML (CXML), and were converted for general use in statistical analysis and displays.

3. Ensuring Homogeneity of Data

Track data obtained from the TIGGE Web site were compiled by groups of models, individual models, all regions, and individual regions. For example, comparisons of data were by all models (ECMWF+UKMET+GFS), by individual model (ECMWF, UKMET, and GFS) and by a combination of models (ECMWF+UKMET). One major challenge in this research was ensuring that all data were homogeneous before conditioning and conducting statistical analyses. When comparing these large datasets from several different ensemble models, it was critical to make sure that similar data were being compared in each group of files. For example, when grouped by all models and all regions, if the GFS did not have a control run for a specific date/time in 2007, but the ECMWF and UKMET did, then that case was eliminated. If the Along-Track Errors (ATE) for the ECMWF were not available for a certain time period, then they were eliminated as well. Each dataset, by virtue of being homogeneous, contained different amounts and types of data compiled from the TIGGE files. This resulted in a dataset that included homogenous model runs (OFC, control (CTL), deterministic (DET), and ensemble mean (EMN)) for the same forecast times (0–120-h), for the same errors (ATE, XTE, FTE), and for each group of models and/or regions.

4. Ensemble Prediction Systems

Different characteristics among the Ensemble Prediction Systems (EPS) used in this study are given in Table 1. Part of the problem behind ensuring a homogeneous dataset is the lack of standardization between ensemble models. For example, the ECMWF has 51 members and is run every 12-hours (00 UTC and 12 UTC) out to 384 hours, the UKMET has 23 members and is run every 12-hours (00 UTC and 12 UTC) out to 144 hours with intermediate runs (01 UTC and 13 UTC) out to 48 hours, and the GFS has 21 members and is run every 6 hours (00 UTC, 06 UTC, 12 UTC, 18 UTC) out to 384 hours. For this research, the 00Z and 12Z runs were used in all cases. In each of these EPSs, the control

(CTL) model is typically the higher resolution deterministic (DET) model from that center, and then an even number ensemble model forecasts, at lower resolution are made from perturbed initial conditions.

Table 1. Comparison of Ensemble Prediction Systems (EPS) examined in this study.

EPS	Members	Frequency	Duration
ECMWF	**51**	**00 UTC, 12 UTC**	**384 h**
UKMET	**23**	**UTC (intermediate), 12 UTC, 13 UTC (intermediate)**	**144 h (48 h)**
GFS	**21**	**00 UTC, 06UTC, 12 UTC, 18 UTC**	**384**

5. Forecast Position Errors

The three types of errors (along-, cross-, and forecast-track) examined in this thesis are shown in Figure 10. The track error of the forecast is determined from the verifying best-track position. The forecast track error (FTE) is the great circle distance between the best-track and forecast positions. In addition, the cross-track error (XTE) and along-track error (ATE) are defined as illustrated in Figure 10.

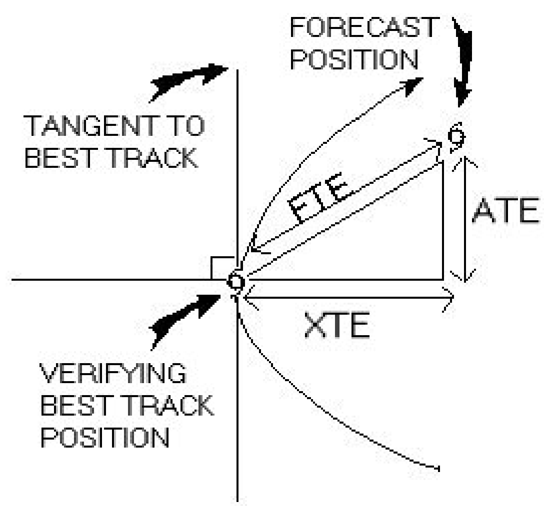


Figure 10. Definition of cross-track error (XTE), along-track error (ATE), and forecast track error (FTE). In this example, the forecast position is ahead of and to the right of the verifying best track position. Therefore, the XTE is positive (to the right of the best track) and the ATE is positive (ahead or faster than the best track) (From Tsui and Miller 1988).

6. Conditioning by Region

Once all ensemble and official track forecast data were combined into homogeneous files, the procedure was then to begin conditioning these data based on certain parameters. Because location was the primary parameter to explore, the North Atlantic Basin was divided into six regions based on latitude and longitude (Figure 11).

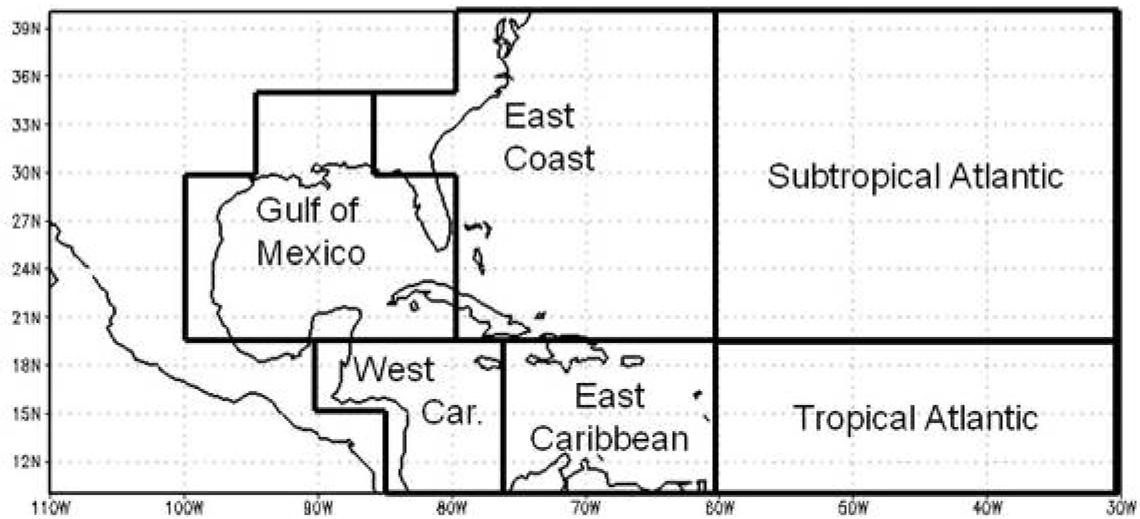


Figure 11. Geographic regions for conditioning Ensemble Prediction System (EPS) TC track errors and spread.

B. STATISTICAL ANALYSIS METHODS

1. Testing for Differences in Mean

While analyses in this thesis are similar in scope to that of Hauke (2006), several differences will be described. In Figure 12, three distributions are examined. The two distributions in the low variability case (bottom row) have very little overlap and thus are significantly different. The distribution in the medium variability case (top row) has some overlap and is only slightly different. In the high variability case (middle row), it becomes more difficult to distinguish the two populations.

In this thesis, the first objective is to search for significant differences among the track forecast error distributions when conditioned on relative physical parameters. If only small differences exist as demonstrated by the high variability case in Figure 12, then there will likely be little improvement in the MC model by including that physical parameter. This is because the distributions are similar, and using them independently will not change the probability output (Hauke 2006). However, it is expected that construction of a conditional probability distribution when significant differences exist in the distributions that have low variability as in Figure 12 will then result in better discrimination in an MC model.

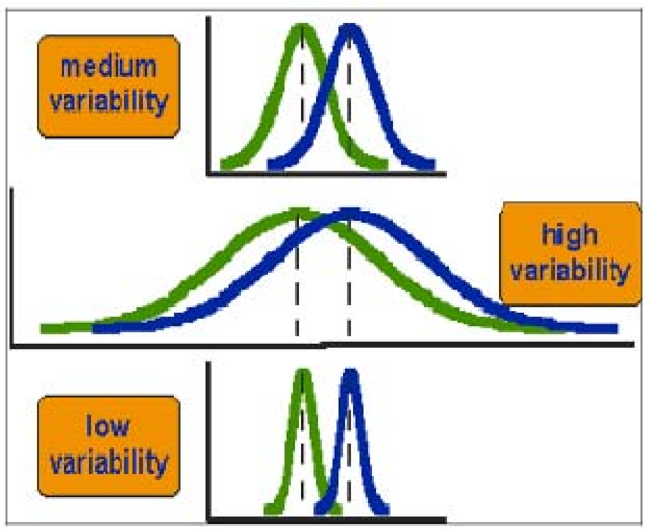


Figure 12. Three pairs of distributions with the same mean (From Trochim 2010).

The objective method to determine if samples from two populations are significantly different is the t-test statistic (T) (Wilks 2006), which is a function of the differences between the two sample means and takes into account the sizes and variances of the distributions. The t-test statistic is defined as

$$T = \frac{\bar{X}_1 - \bar{X}_2 - \mu_0}{\sqrt{\frac{S_1^2}{n_1} + \frac{S_2^2}{n_2}}} \tag{1}$$

where $\bar{X}_1$ and $\bar{X}_2$ are the means of the two samples, $\mu_0 = \mu_1 - \mu_2 = 0$ is the hypothesized difference between the two means. In Equation (1), S_1 and S_2 are the standard deviations of the two samples, and n_1 and n_2 are the numbers of members in each sample. The t-statistic is evaluated using a .05 percent confidence level, which means the test will be in error no more than five out of 100 times (Wilks 2006).

The null hypothesis for this test is that the two means are the same ($\mu_1 - \mu_1 = 0$) (Figure 13). If the null hypothesis is true, then the t-statistic will fall in the acceptance region of the t-distribution (t-statistic < t-critical). If the null hypothesis is false, then the t-statistic will fall in the critical region of the t-distribution (t-statistic > t-critical).

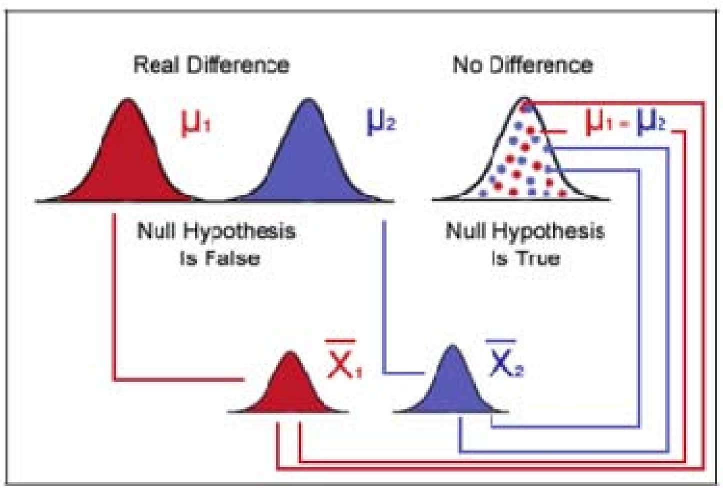


Figure 13. Hypothesis test for differences in the means of two distributions. (From Wadsworth 2010).

As indicated in Figure 12, the means of two samples may be the same while the variances are different. This situation may apply with cross- and along-track forecast errors since the errors are both positive and negative and thus tend to cancel at times, which may then lead to very small differences between the distributions. However, the means of the distributions can be used as an indicator of the skewness. Using different distributions that have the same mean but different variances also makes them separable and may also improve the MC product (Hauke 2006).

2. Histograms and Probability Distribution Function (PDF) Plots

Quantitative results of this thesis are presented primarily in the form of histograms and probability distribution functions. The purpose of these visual representations of the data is to clearly and accurately convey useful information as a result of comprehensive data analysis.

Several histograms and probability distribution functions are presented in this thesis to provide useful data summaries that convey the following information: the general shape of the frequency distribution (normal, chi-square, etc.), symmetry of the distribution or whether it is skewed, and modality (unimodal, bimodal, or multimodal). Frequency distribution histograms can be converted to a probability distribution using several methods. Dividing the tally in each group by the total number of data points defines the relative frequency. Then, maximum likelihood estimates (Wilks 2006) can be used to define the probability distribution function for a specific distribution form. The shape of the distribution conveys important information such as the probability distribution of the data (Netmba 2010). In this thesis, histograms and PDFs are used to determine the statistical character of forecast errors for each forecast interval.

THIS PAGE INTENTIONALLY LEFT BLANK

IV. ANALYSIS AND RESULTS

A. INTRODUCTION

The goal of this thesis is to demonstrate the likely benefit to the probability model based on conditioning the track error distributions from which the MC model draws. The primary conditioning factor to be examined is TC location at the time a forecast is issued. If a storm is located in a particular region then it may be beneficial for the probabilistic model to draw from historic track errors that were produced in the same region.

In addition to geographic regions, error distributions from specific model products are examined relative to the error distribution of the official forecast (OFC). For each EPS, the errors in ensemble mean (EMN) forecast are compared to the OFC track errors. The control forecast (CTL) track errors were not available for all models at all times. Therefore, track errors for the CTL forecasts are not used in the study. However, the deterministic (DET) model forecast track errors are compared to the OFC and EMN forecast track errors. As defined in Chapter III, the homogeneous data are grouped based on model (all models, ECMWF, UKMET, ECMWF+UKMET, and GFS), by region (GOM, ECS, SBA, WCB, ECB, and MDR as in Figure 11), by error (ATE, XTE, and FTE), and by forecast interval (12, 24, 36, 48, 60, 72, 96, and 120-h).

To determine whether conditioning based on geographic location was warranted, the homogeneous data groupings are examined to identify significant differences in statistical characteristics among the groups. The mean and standard deviations of ATEs, XTEs, and FTEs for EMN, DET, OFC, and CTL members of each data group are computed. Tests are then conducted to determine statistical differences among these errors in model and geographic groups. For combinations of model groups and geographic regions, the EMN errors were compared to OFC errors, the DET errors were compared to OFC errors, and the EMN errors were compared to the DET errors. The probability distribution functions (PDFs) defined by ATEs and XTEs of EMN, OFC, and DET for all regions and all models were then created.

B. STATISTICAL SIGNIFICANCE BY MODEL AND REGION

Bar charts are used to compare the geographic regions, model groups, and errors. The abscissa represents the forecast interval from 0-120 hours and the ordinate represents statistical significance. A positive oriented bar identifies positive differences between respective errors that are considered to be statistically significant. A negative oriented bar identifies a negative difference that is statistically significant.

1. Analysis and Results

For the entire data set of all models and all regions, the ATEs, XTEs, and FTEs of the EMN are significantly greater than the OFC ATEs, XTEs, and FTEs for most forecast intervals at a significance level of 0.05 (Figure 14). The ATEs, XTEs, and FTEs of the DET are also significantly greater than OFC ATEs, XTEs, and FTEs for several forecast intervals. The smaller OFC forecast errors than both the EMN and DET forecasts indicates the NHC forecasters are adding value to their guidance. The ATEs and FTEs of the EMN were greater than ATEs and FTEs of the higher resolution DET for shorter range forecasts between 12–60-h.

Because one or more track forecast error types are significantly greater than the OFC forecast, it is worthwhile to investigate if any specific geographic region(s) contributes most to these errors (Figure 15). The significantly larger EMN errors than the OFC errors at 48-h and beyond in the All Regions group (Figure 14) seem to be due to errors from the ECB (Figure 15e), MDR (Figure 15f), ECS (Figure 15b), and WCB (Figure 15d). Significantly greater EMN errors than OFC errors do exist in the GOM region, but primarily at forecast intervals between 12–60-h. Therefore, some evidence is found that the forecast track errors from the combination of all models EMN in different regions may contain additional information from only the OFC track errors.

In regional comparisons of the All Models DET and OFC track errors (Figure 14 middle panel), much more variability exists in that the significant differences in Figure 14 mainly come from the main development region (Figure 15f, middle panel). Similarly, the differences between the All Models DET and EMN track errors over All Regions (Figure 14, bottom panel), are mainly from the main development region (Figure 15f, bottom panel).

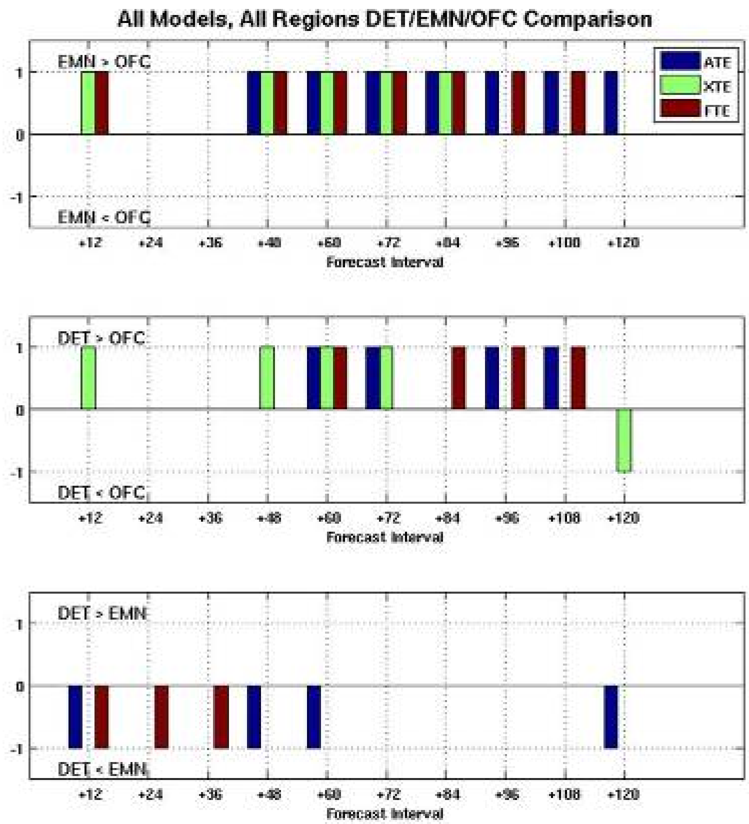


Figure 14. Statistically significant (at a level of 0.05) differences in ATE, XTE, and FTE (see designations on the right side of the top panel) for the sample of all models and all regions. EMN and OFC errors (top), DET and OFC (middle), and DET and EMN (bottom) are given as a function of forecast interval (h). The positive (negative) bar values identify statistically significant differences as defined by the labels in each panel.

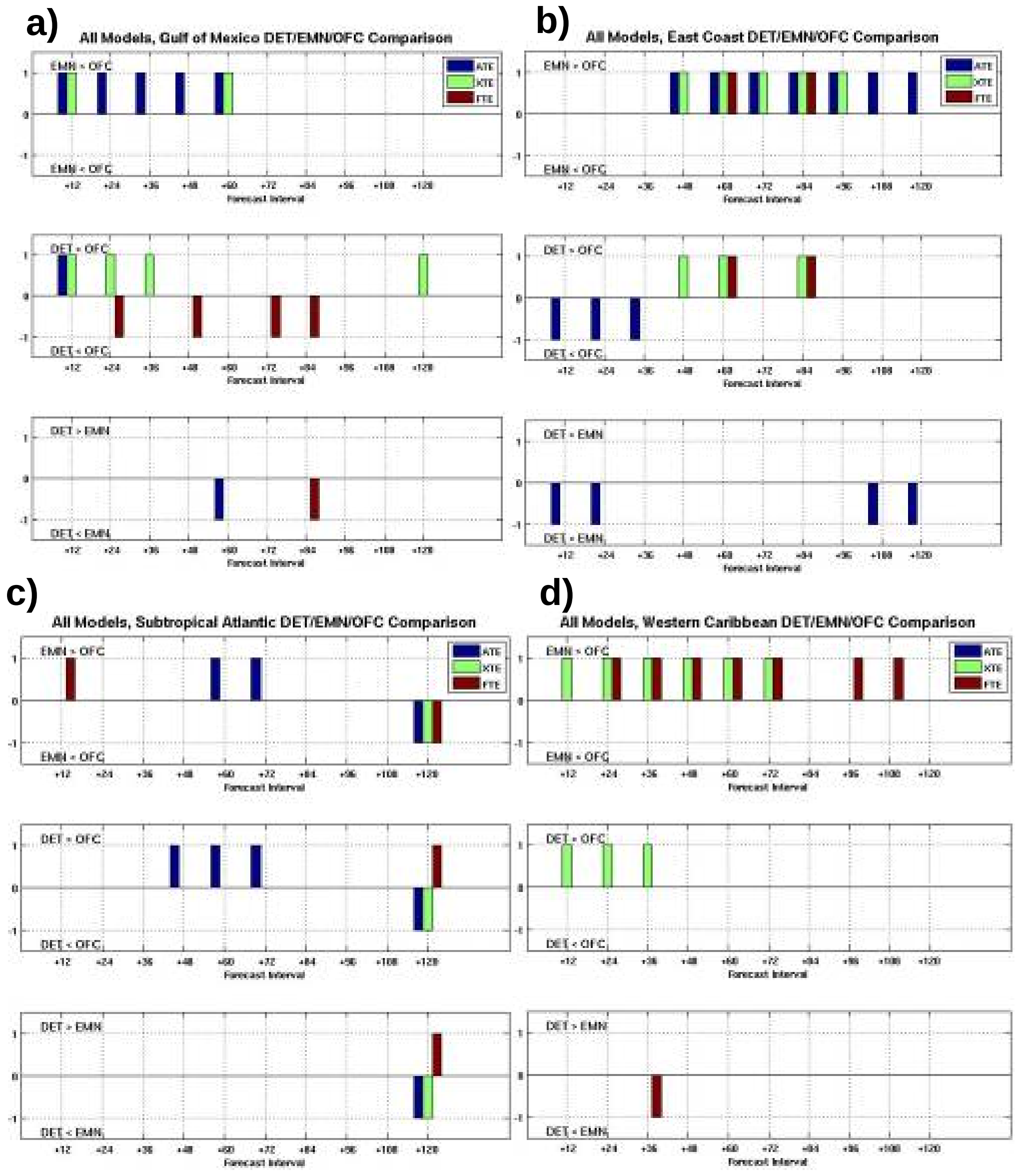


Figure 15. Statistically significant (at a level of 0.05) differences in ATE, XTE, and FTE (see designations on the right side of the top panel) for the sample of all models in (a) the Gulf of Mexico, (b) the east coast region, (c) the subtropical Atlantic, (d) the western Caribbean, (e) the eastern Caribbean, (f) and the main development region. EMN and OFC errors (top), DET and OFC (middle), and DET and EMN (bottom) are given as a function of forecast interval (h). The positive (negative) bar values identify statistically significant differences as defined by the labels in each panel.

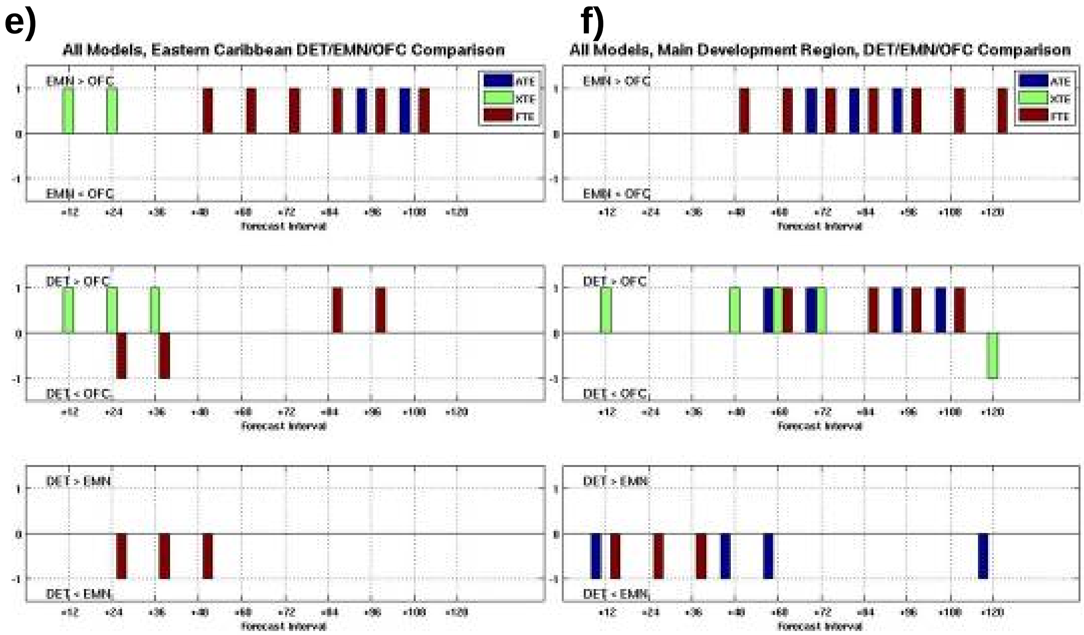


Figure 15 Continued.

For the combination of ECMWF and UKMET models, the EMN XTEs and FTEs in the WCB contribute most to All Models, All Regions errors in Figure 14, while few errors from the SBA contribute. The EMN FTEs and ATEs in the ECB and MDR contribute significantly to All Models, All Regions EMN errors (Figure 15), and DET ATEs, XTEs, and FTEs contribute to All Models, All Regions DET errors.

Because forecast availability for the GPS ensemble prediction system is less than for the ECMWF and UKMET, a second group was created by combining the ECMWF and UKMET models only (Figure 16). A similar pattern is evident in that the EMN FTEs are significantly larger than the OFC errors for forecast intervals greater than 48-h (Figure 16a, top panel). The DET track errors are also significantly greater than OFC track errors for intervals greater than 48-h (Figure 16, middle panel). There are not many significant differences between EMN and DET forecast errors (Figure 16a, bottom panel).

Whereas it is clear that the majority of the significant error differences are in either the ATEs or FTEs, only rarely are significant differences found in the EMN, DET, and OFC XTEs. Consequently, the paths of the TCs are generally predicted without a bias, and the ATE is the major source of the FTE.

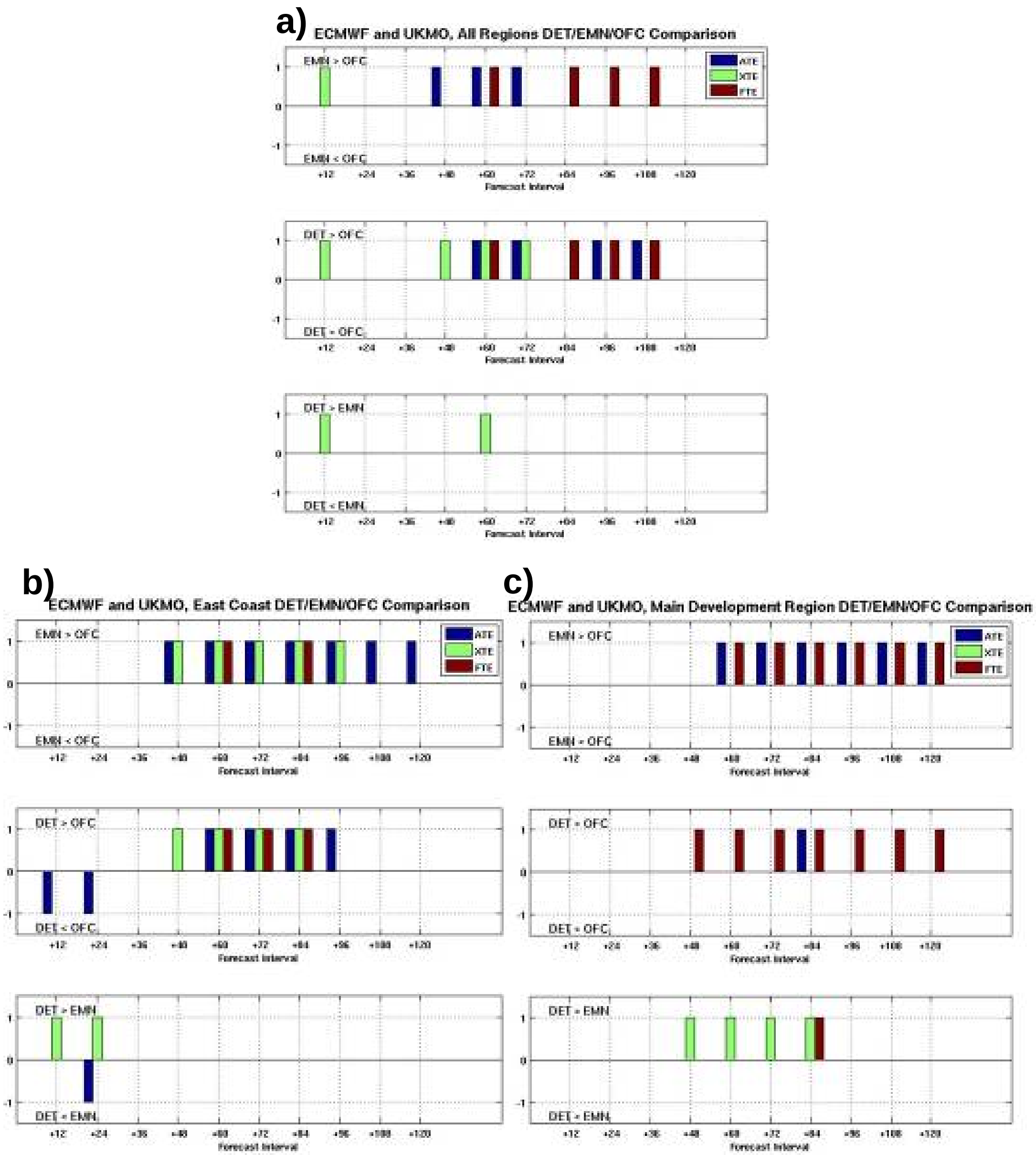


Figure 16. Statistically significant (at a level of 0.05) differences in ATE, XTE, and FTE (see designations on the right side of the top panel) for the combination of ECMWF and UKMET in (a) all regions, (b) the east coast region, and (c) the main development region. EMN and OFC errors (top), DET and OFC (middle), and DET and EMN (bottom) are given as a function of forecast interval (h). The positive (negative) bar values identify statistically significant differences as defined by the labels in each panel.

Comparison of the combined ECMWF and UKMET model forecasts for individual regions relative to all regions (Figure 16a) indicates that the significant errors are mainly from the ECS region (Figure 16b) and MDR (Figure 16c). Other regions (not shown) do not contain consistent track error distribution differences from all regions.

Individual model forecasts are also examined for all regions and then compared to errors in each region. For the ECMWF forecasts only, significant differences exist between the EMN and the OFC errors at nearly every forecast interval for all regions (Figure 17a, top panel). Again, the significantly larger EMN errors are typically in the ATE and FTE values. Examination of the errors in the other regions (not shown) indicates that the majority of the significant EMN differences compared to OFC errors are for the eastern Caribbean (Figure 17b, top panel).

The ECMWF DET errors also are significantly larger than the OFC errors for most forecast intervals (Figure 17a, middle panel). However, these error differences do include XTE at shorter forecast intervals. Furthermore, no one region contributes to the differences defined in the All Regions group (not shown). It is noteworthy that no significant differences in even the XTEs exist between the ECMWF DET and the EMN in the ECB (Figure 17b, bottom panel).

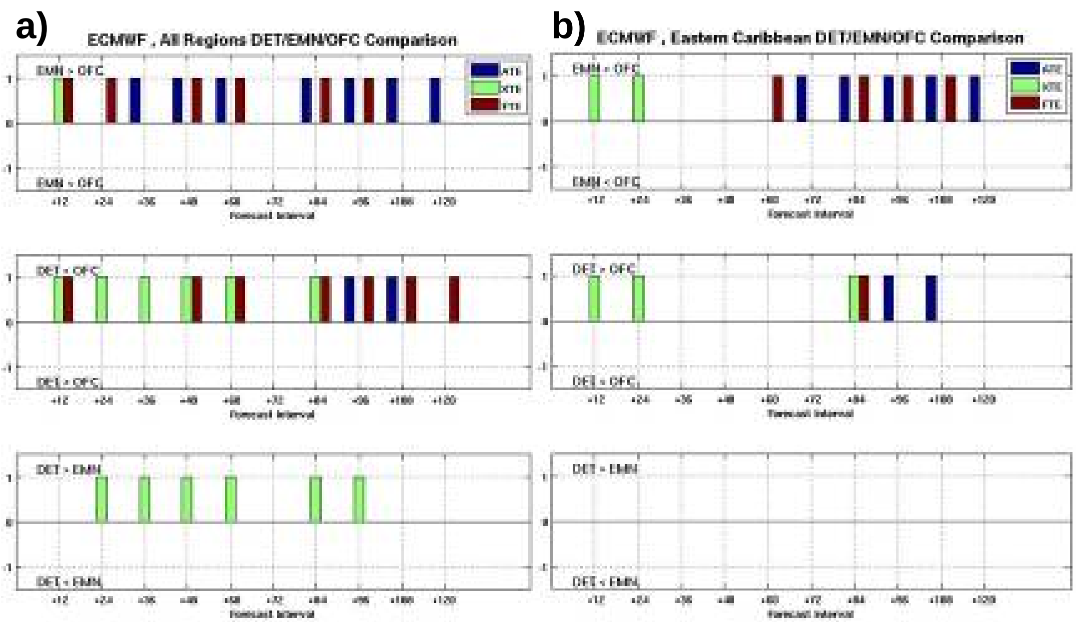


Figure 17. Statistically significant (at a level of 0.05) differences in ATE, XTE, and FTE (see designations on the right side of the top panel) for the ECMWF in (a) all regions and (b) the eastern Caribbean. EMN and OFC errors (top), DET and OFC (middle), and DET and EMN (bottom) are given as a function of forecast interval (h). The positive (negative) bar values identify statistically significant differences as defined by the labels in each panel.

Of all models, the UKMET had the fewest number of EMN and DET track errors (Figure 18a) that were significantly greater than OFC track errors when all regions are combined. However, the EMN track forecast errors over the main development region are significantly greater than the OFC errors (Figure 18b, top panel). Also, the significant differences are only FTEs and ATEs, so again the path is consistently forecast, but the spread along the path contributes to the errors. There are also some significantly larger DET errors than OFC errors in the main development region (Figure 18b, middle panel).

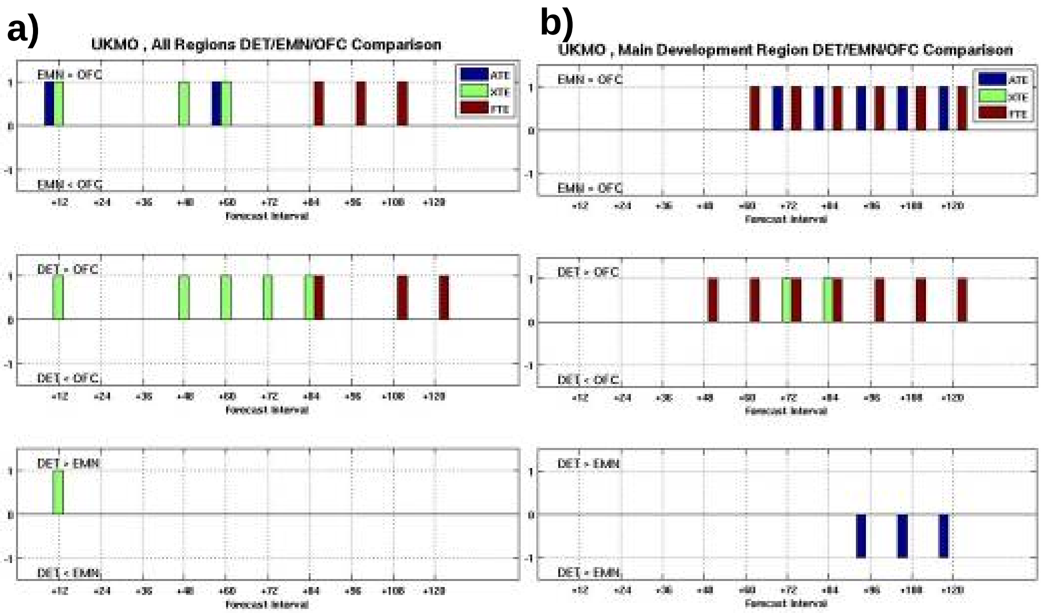


Figure 18. Statistically significant (at a level of 0.05) differences in ATE, XTE, and FTE (see designations on the right side of the top panel) for the UKMET in (a) all regions and (b) main development region. EMN and OFC errors (top), DET and OFC (middle), and DET and EMN (bottom) are given as a function of forecast interval (h). The positive (negative) bar values identify statistically significant differences as defined by the labels in each panel.

At almost all forecast intervals, the GFS EMN XTEs and FTEs were significantly greater than the OFC and DET errors for all regions (Figure 19a). The consistently larger GFS EMN XTEs and FTEs than the GFS DET errors (Figure 19a, bottom panel) indicates a significant degradation of the EMN tracks relative to the higher resolution DET model tracks. These errors primarily originated from the MDR (Figure 19b). Other regions (not shown) did not contain significantly large errors relative to All Regions.

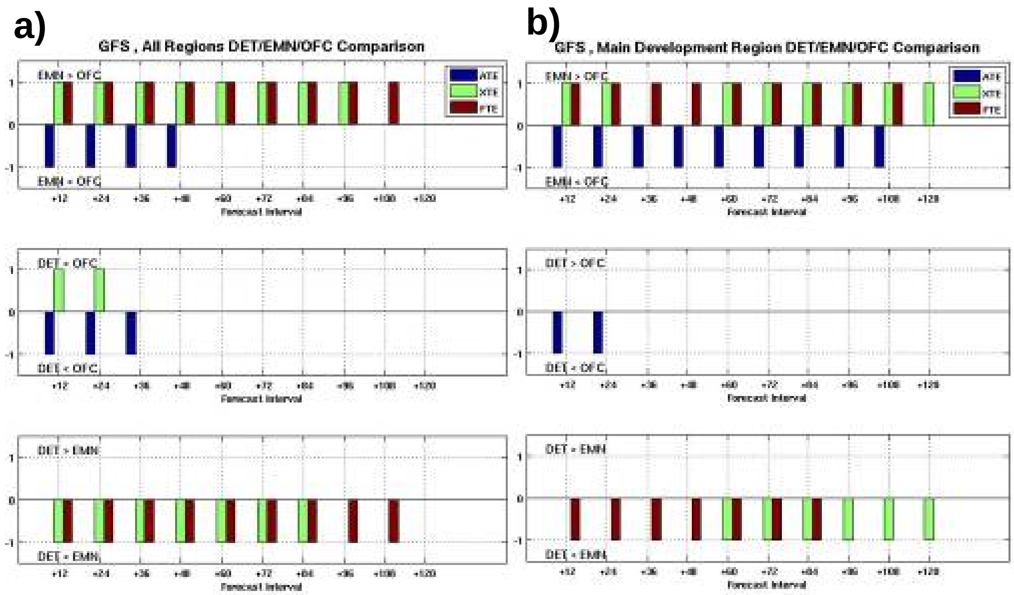


Figure 19. Statistically significant (at a level of 0.05) differences in ATE, XTE, and FTE (see designations on the right side of the top panel) for the GFS in (a) all regions and (b) main development region. EMN and OFC errors (top), DET and OFC (middle), and DET and EMN (bottom) are given as a function of forecast interval (h). The positive (negative) bar values identify statistically significant differences as defined by the labels in each panel.

2. Summary

As expected, EMN track errors were frequently larger than OFC track errors for all regions and all models. The EMN track errors were frequently larger than DET errors, and each of these was greater than OFC track errors.

The individual regions that contributed the most significant EMN and DET errors compared to the OFC errors for the All Models group were the ECB, MDR, and ECS. This error characteristic was also true for the ECMWF+UKMET group. For the ECMWF, the ECB region contributed the most to the error differences with the OFC forecasts. The MDR had the largest contribution to the UKMET forecast error differences and also to the GFS forecast error differences.

A climatologically typical TC track from the Cape Verde Islands transits westward through the entire MDR, crosses part of the ECB, and then recurves northward and eastward through the ECS. The high frequency of storms during the 2007-2009 Atlantic hurricane seasons that moved along this typical TC track was most likely the reason these three regions observed the most forecast errors. Fewer cases were available in the GOM, WCB, and SBA as fewer storms crossed these regions. However, the consistent contribution from MDR, ECB, and ECS regions in defining significant differences with OFC errors suggest that error distributions associated with these regions may be useful in defining probability distributions for tropical cyclone forecasts.

C. PROBABILITY DENSITY FUNCTIONS BY MODEL AND REGION

Based on the results of significant differences among model ensembles, deterministic, and official forecasts over all regions and individual regions, the probability distribution functions (PDF) of the forecast error distributions are analyzed. Significant differences in the PDF characteristics would imply that the probability model could be impacted by the use of these distributions. Because the majority of significant differences in Section B are in the ATEs, these errors are examined first. The PDFs of FTEs are not examined since only ATEs and XTEs are used in the probabilistic model. Only selected forecast intervals will be described in this chapter. The characteristics for the remaining forecast intervals are available in the Appendix.

1. ATE Probability Distribution Functions

Comparison of the EMN and OFC 12-h ATEs (Figure 20) indicates that the EMN error distribution in the ECB region has a much larger variance than the error distribution for the All Regions. Therefore, the EMN forecasts over the ECB have significantly different distributions than the ATEs in other regions with a standard deviation of 50 km for the All Regions (Figure 20a, box). By contrast, the probability distribution functions for the 12-h OFC forecasts (Figure 20b) in the All Regions and the individual regions are similar, with standard deviations ranging from 30 km to 59 km, which is again associated with the ECB region.

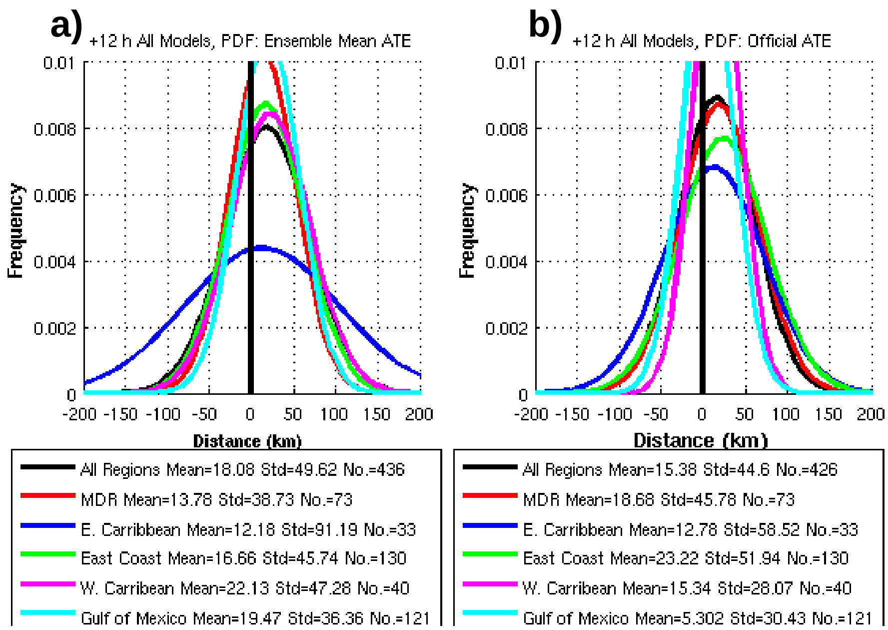


Figure 20. Normal probability distribution functions for the 12-h forecast ATEs by the (a) EMN and (b) OFC for the group of All Models. The abscissa is the positive or negative ATEs in kilometers, and the ordinate represents frequency of occurrence. Curves are color-coded by region (see box) with the mean, standard deviation, and number of members shown in the legend.

The PDFs for the 48-h EMN and OFC forecast ATEs are similar to the 12-h PDFs except that the magnitudes are larger (Figure 21). Notice the distinctly larger spread in the ECB region (Figure 21a) relative to the All Regions and the other regions. For these 48-h forecasts, the standard deviation in the ECB is 225 n mi versus 136 n mi for the All Regions and a range from 76 km to 150 km for the other regions. Whereas the PDFs for the 48-h OFC forecasts in the All Regions and all other regions besides the ECB region are quite similar (Figure 21b), the OFC PDF for the ECB region is distinct. Indeed, the OFC standard deviation in this region is almost the same as for the 48-h EMN (209 km versus 225 km).

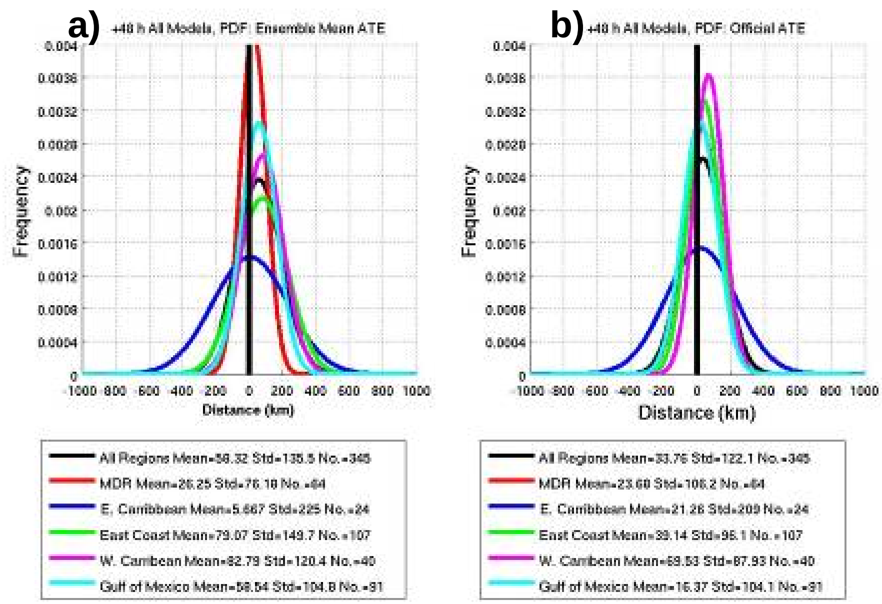


Figure 21. Normal probability distribution functions for the 48-h forecast ATEs by the (a) EMN and (b) OFC for the group of All Models. The abscissa is the positive or negative ATEs in kilometers, and the ordinate represents frequency of occurrence. Curves are color-coded by region (see box) with the mean, standard deviation, and number of members shown in the legend.

Beyond 48-h, the PDFs have larger spreads and increases in standard deviations of the EMN and the OFC ATEs (Figure 22). The ECS region has significantly less variability than the All Regions PDF of OFC ATEs (Figure 22b). Note the large EMN spread in the GOM. This could be a result of the usually slow pace of storms in this region and the associated difficulty in forecasting the path at the +84-h forecast interval.

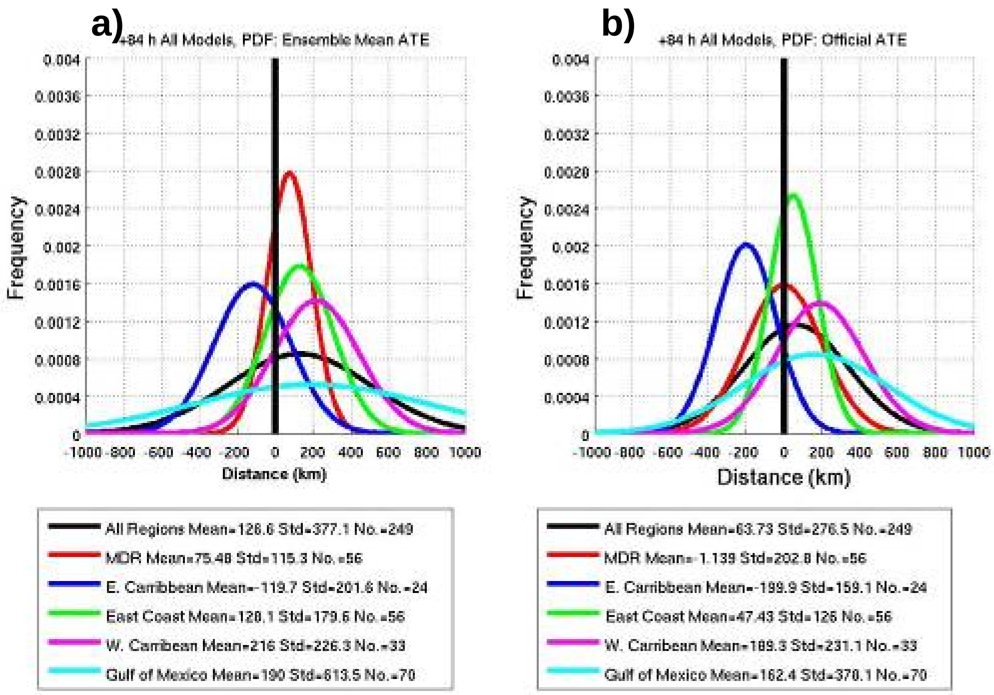


Figure 22. Normal probability distribution functions for the 84-h forecast ATEs by the (a) EMN and (b) OFC for the group of All Models. The abscissa is the positive or negative ATEs in kilometers, and the ordinate represents frequency of occurrence. Curves are color-coded by region (see box) with the mean, standard deviation, and number of members shown in the legend.

At +120-h, the ECB, MDR, and ECS regions have smaller standard deviations about the EPS mean ATE than for the All Regions. Indeed, the ECB and MDR have ATE standard deviations that are less than half of the standard deviation of the All Region ATEs. These small standard deviations indicate a small variability in the storm translation speeds in these regions even at five days, which probably arises due to the African Easterly waves having consistent, predictable paths and translation speeds. The ECS and MDR regions also have significantly less variability than the all regions PDF of OFC ATE errors (Figure 23b). Recall that these regions also contributed most to the significantly larger EMN track errors compared to the OFC track errors.

While the results of the t-test analyses for the all models and all regions groups in Chapter IV.B indicates significant differences between EMN and OFC beyond 48-h, the PDFs of ATEs do not become significantly different in terms of variance until 84-h and beyond. Therefore, it appears that conditioning for the ATE in these regions for the all model group would not improve the MC probability model until beyond the 72-h forecast interval.

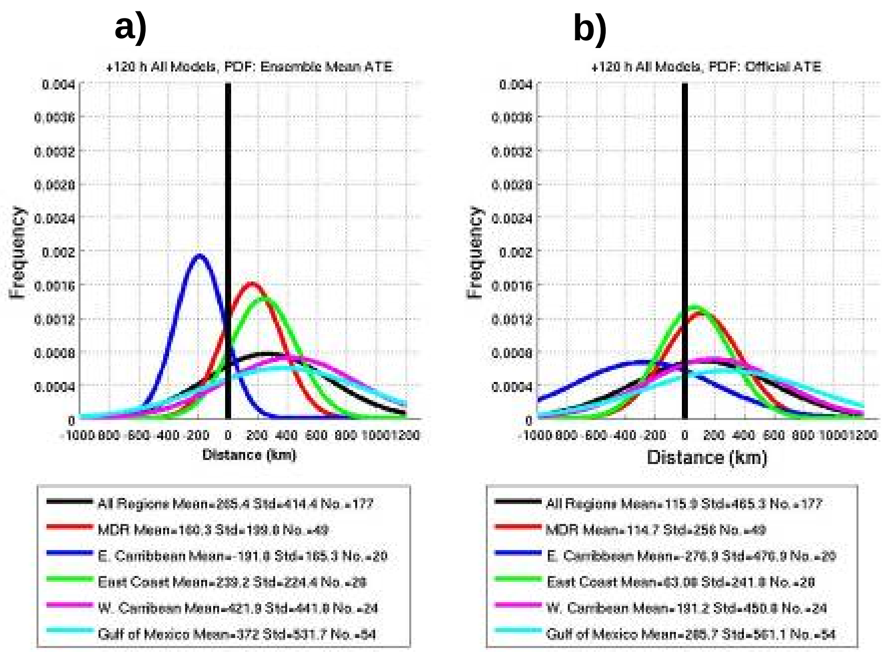


Figure 23. Normal probability distribution functions for the 120-h forecast ATEs by the (a) EMN and (b) OFC for the group of All Models. The abscissa is the positive or negative ATEs in kilometers, and the ordinate represents frequency of occurrence. Curves are color-coded by region (see box) with the mean, standard deviation, and number of members shown in the legend.

2. XTE Probability Distribution Functions

Not many significant differences were found between the mean EMN and OFC XTEs (Figures 14 and 15) as were found between the EMN and OFC ATEs. For example, recall that the variance of the EMN XTE All Regions group at 24-h is larger than the All Regions group of the OFC XTE distribution (Figure 14). However, some differences were found in the PDF characteristics for the EMN and OFC XTEs. It is clear in Figure 24a that the PDFs associated with XTEs in the 24-h EMN forecasts of the All Models groups begins to vary much more than the OFC XTE distributions (Figure 24b). However, the variance in the EMN XTE PDF for the ECB region does not increase as rapidly with forecast interval as the variance in ATE (Figure 20a).

By 120-h, many of the probability distribution functions of the OFC XTEs for several of the individual regions have less variance than the All Regions group (Figure 25b). However, the main contribution to the larger variance in the OFC XTE All Regions group comes from the MDR, which has a larger negative bias and a larger variance. The PDFs of EMN XTEs at 120-h have means and variances that are quite similar (Figure 25a), even though the mean differences between EMN XTE and OFC XTE were not significantly different for the All Regions group (Figure 14) or for any regional group (Figure 15). The variances are significantly larger for the ECB and ECS region.

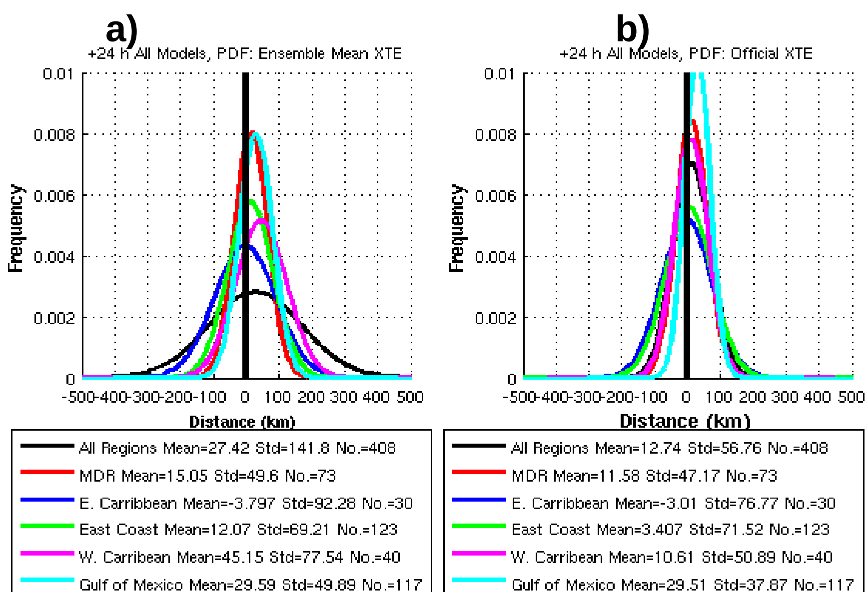


Figure 24. Normal probability distribution functions for the 24-h forecast XTEs by the (a) EMN and (b) OFC for the group of All Models. The abscissa is the positive or negative XTEs in kilometers, and the ordinate represents frequency of occurrence. Curves are color-coded by region (see box) with the mean, standard deviation, and number of members shown in the legend.

The GOM region was the only region in which the OFC XTE variance was significantly larger than the EMN variance (Figure 24). The GOM was the only region in which the OFC XTE variance was larger than the variance in All Regions.

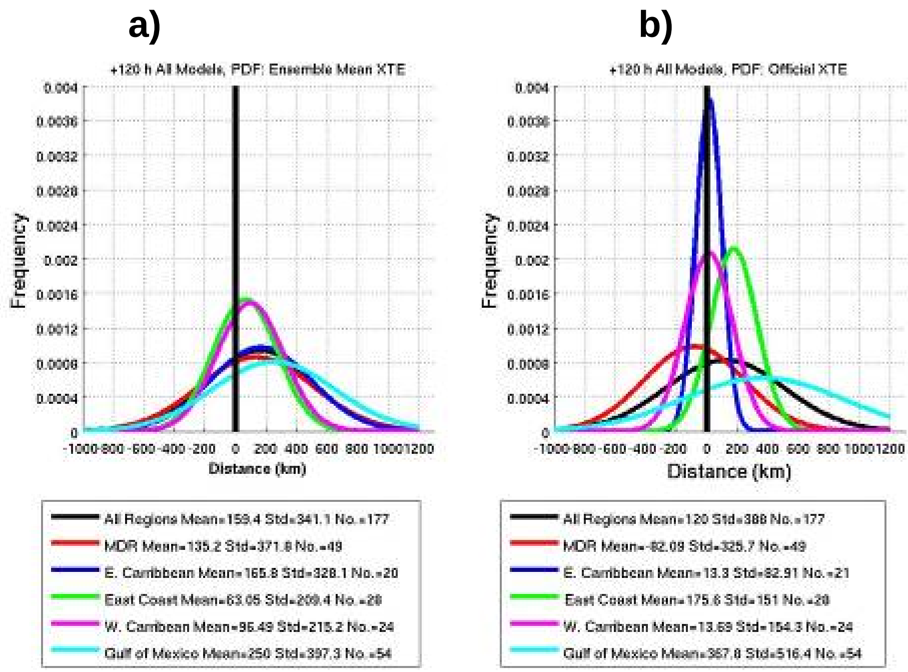


Figure 25. Normal probability distribution functions for the 120-h forecast XTEs by the (a) EMN and (b) OFC for the group of All Models. The abscissa is the positive or negative XTEs in kilometers, and the ordinate represents frequency of occurrence. Curves are color-coded by region (see box) with the mean, standard deviation, and number of members shown in the legend.

3. Testing for Sensitivity

Testing the sensitivity of various error distribution characteristics is necessary to determine which distributions improve the Wind Speed Probability Forecast Products created by DeMaria et al. (2009). The test product should be similar in framework, but modified slightly. Error distributions would be defined that are associated with ATEs and XTEs of for selected forecast combinations and regions, such as the official tracks, All Models, ECMWF and UKMO combined, and ECMWF, UKMO, and GFS individually. Differences in probabilities could be evaluated among groups and regions, and these distributions could be evaluated to fit various functional forms. Differences related to distribution characteristics could then be tested, and once the “best” fit is defined, then serial correlation could be identified. The next step would be to evaluate differences among groups and regions and define residual distributions for sampling. Once a sampling technique is determined, then intensity estimates via linear model fit could be applied, and serial correlation and track-intensity dependence could be accounted for. The last step would be to apply the wind distribution model and define probabilities.

4. Summary

Analysis of the PDF characteristics associated with the All Models group has resulted in identification some basic differences among the distributions of XTEs and ATEs of the EMN and OFC track forecasts. As a first approximation, the normal distribution has been fit to the two error measures. This choice is based on analysis of DeMaria et al. (2009) and Majumdar and Finnochio (2010) in which normal distributions were used to define ATE and XTE characteristics associated with OFC and EMN forecasts. The All Models group was examined because this group provided the most robust comparison of ensemble systems to compare with the OFC forecasts (Figures 14 and 15). Furthermore, it was anticipated that a combination of models would more likely yield a normal distribution of ATEs and FTEs.

As defined by DeMaria et al. (2009), the character of the error distribution from which the Monte Carlo method samples will determine the probability swath for distribution of threshold wind values such as tropical storm/gale or hurricane force. As Hauke (2006) showed, conditioning on expected forecast difficulty produced distributions such that the variability decreased with increased forecast confidence. Therefore, the probability swath was shown to be narrower in high-confidence forecasts. The hypothesis being investigated in this thesis is that additional refinement of key probability distributions could be gained by conditioning on the individual six regions. The distributions defined in Figures 14-26 do demonstrate that statistically significant differences exist between EMN, DET, and OFC track forecasts. In most cases, the EMN mean ATEs and XTEs are significantly larger than OFC errors. Furthermore, the DET errors are larger than the OFC errors but less than the EMN errors. Therefore, it appears that using forecast track error distributions based on EMN or DET forecasts would not sharpen the distributions from which the Monte Carlo sampling is drawn.

Additionally, the normal PDFs of EMN ATE and XTE, and OFC ATE and XTE do indicate a large variation in variance for the distributions. Distributions defined by the DET errors (not shown) are similar to those for the EMN errors. To determine if conditioning by region would refine the PDFs for the MC probability model, the variances between OFC and EMN error distributions are examined. The F-test for equal variances between two probability distributions was used to examine whether differences in variances exhibited in Figures 20–25 are significantly different. In particular, it is important to identify which regions have error distributions that have significantly less variance than the All Regions group for the OFC and EMN forecasts.

Comparison of variances among OFC forecast XTE distributions from individual regions indicates significantly less variance in forecast distributions from the WCB and ECS regions compared to the All Regions group (Table 2). A significant difference in variance is not found between the MDR and All Regions distributions or the ECB and all region distributions. There is less variance in the GOM XTE distribution than the OFC XTE distribution, but this is only true for short-range forecasts (Table 2). At longer forecast intervals, the OFC XTE variance for all regions is less than that for the GOM region only.

Table 2. Results of the F-test for the differences in variances between the All Models/All Regions group and All Models/individual regions groups of OFC XTEs. A shaded (hatched) cell indicates that the variances are significantly different and the All Regions group variance is less (more) than the individual region variance.

F-Test for Variance between OFC XTEs (All Regions) and OFC XTEs (Individual Regions)					
Forecast Interval	MDR	ECB	WCB	GOM	ECS
12					
24					
36					
48					
60					
72					
84					
96					
108					
120					

Table 3. Results of the F-test for the differences in variances between the All Models/All Regions group and All Models/individual regions groups of OFC ATEs. A shaded (hatched) cell indicates that the variances are significantly different and the All Regions group variance is less (more) than the individual region variance.

F-Test for Variance between OFC ATEs (All Regions) and OFC ATEs (Individual Regions)					
Forecast Interval	MDR	ECB	WCB	GOM	ECS
12					
24					
36					
48					
60					
72					
84					
96					
108					
120					

The character of the variance in ATE PDFs (Table 3) is fundamentally different from the XTE distribution variances (Table 2). The distributions conditioned on individual regions have smaller variances in ATEs at short forecast ranges over the GOM and WCB regions. At longer forecast intervals, the variances from distributions defined from the MDR and ECS regions become less than the OFC ATE errors from the All Regions, which is currently used in the MC probability model (DeMaria et al. 2009).

The collections of XTEs and ATEs for the All Regions group do not fit a normal distribution at any forecast interval (first columns in Tables 4 and 5, respectively. For individual regions and XTEs, only shorter range forecasts over the ECS are significantly non-normal. However, nearly all distributions of ATEs are non-normal (Figure 26).

It is possible that the relatively small dataset limited by the TIGGE data availability causes the error distributions to be non-normal. However, examination of other distributions of ATEs, e.g., Figure 26a, indicates that most contain extreme values. Therefore, an extreme-value type of distribution may be more appropriate for fitting to forecast track errors.

Table 4. Results of the chi-square tests for goodness of fit of the OFC XTEs to a normal distribution. Shaded cells define forecast interval and region for which the hypothesis of a good fit to a normal distribution is rejected at the 0.05 level. Cells with vertical lines define forecast intervals and regions for which the data sample was too small to meet cell population requirements for the chi-square test.

Chi-Square Goodness of Fit for OFC XTEs to a Normal Distribution						
Forecast Interval	All Regions	MDR	ECB	WCB	GOM	ECS
12						
24						
36						
48						
60						
72						
84						
96						
108						
120						

Table 5. Results of the chi-square tests for goodness of fit of the OFC ATEs to a normal distribution. Shaded cells define forecast interval and region for which the hypothesis of a good fit to a normal distribution is rejected at the 0.05 level. Cells with vertical lines define forecast intervals and regions for which the data sample was too small to meet cell population requirements for the chi-square test.

Chi-Square Goodness of Fit for OFC ATEs to a Normal Distribution						
Forecast Interval	All Regions	MDR	ECB	WCB	GOM	ECS
12						
24						
36						
48						
60						
72						
84						
96						
108						
120						

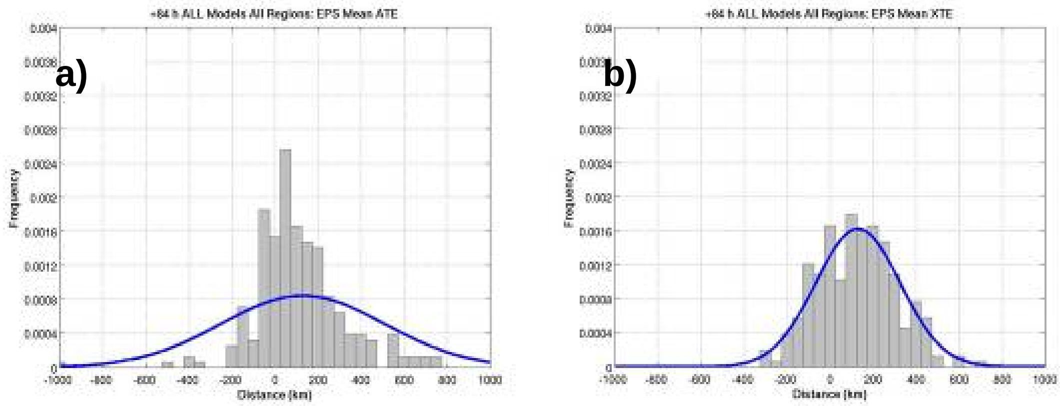


Figure 26. Distribution of ATEs (a) and XTEs (b) for all models, all regions at the +84-h forecast.

It is important to examine how appropriate a normal distribution as a base PDF is for use in probability models. As an example, a normal PDF is fit to 84-h EMN ATE and XTE errors and displayed in Figure 26. It is clear that the distribution of ATE errors does not fit a normal distribution while the distribution of XTEs seems to fit the normal distribution quite well. To examine the use of the normal distribution for OFC track error distributions defined above in the variance comparison, a chi-square goodness of fit test is applied to the normal PDFs and OFC XTE and ATE data (Tables 4–5).

THIS PAGE INTENTIONALLY LEFT BLANK

V. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

This study was the first step in an investigation of whether the MC probability model would be improved by conditioning the TC track error distribution on storm location rather than on basin-wide error statistics. If it is possible to use different track error distributions for different storm locations, the probability wind output may have more utility to decision makers. The goal is to then improve TC track forecasts that ultimately result in decreasing societal and physical impacts to both civilian and military entities.

The initial step was to test three seasons of ensemble model track error distributions (EMN and DET) to see if they are significantly different from the official (OFC) track error distributions. The homogeneous data were grouped based on individual models, groups of models, and by region. Significant differences in statistical characteristics were then identified among the groups to determine whether conditioning based on geographic location was warranted. Once the means and standard deviations of all errors for each group of data were computed, tests were then conducted to determine statistical differences among the error distributions in model and geographic groups. The EMN, OFC, and DET errors were intercompared for combinations of model groups and geographic regions.

Examination of each regional distribution for each forecast interval suggests that differences in distributions existed for ATEs and XTEs. However, these differences vary by forecast interval and regions. Because errors for EMN and DET forecasts typically have larger mean errors and larger variances than OFC forecast errors, it is unlikely that independent error distributions based on these models would refine the PDFs used in the probabilistic model. However, this should be tested with a sensitivity analysis and verified with a probability swath. It is possible that a combination of PDFs from the OFC and the EMN forecasts would provide a more complete probabilistic representation of the wind distributions. Although no consistent patterns were found with respect to variance comparisons between ATE and XTE OFC error distributions over all regions and individual regions, enough evidence was presented that warrants testing of conditional distributions based on region in the MC probability model.

Finally, the lack of fit to a normal distribution associated with most of the probability distributions suggests that alternative distribution functions may improve the probability model. However, the relatively small sample of only three years available to this study may adversely impact the tests of distribution fit. Additional sensitivity testing in a MC probability model is required to determine how these distributions would impact the WPFP.

Based on the results of this study, it is expected that the refinement of current distributions of forecast track errors based on conditions derived from specific parameters such as ensemble spread or storm location should improve NHC tropical cyclone probabilistic wind distribution forecasts.

B. RECOMMENDATIONS

The next step should be to change the MC model code to draw from along-track and cross-track error distributions based on region instead of just one error distribution for all track forecast situations and regions. The model should then be tested to see if the probabilistic wind distribution accuracy is significantly improved. If so, the operational MC model should be modified to include these additional parameters.

Future research should concentrate on other factors that may influence historic track error distributions. Some of these factors may be steering flow characteristics, storm intensity, and weather regime of the eastern U.S. Historical TIGGE data are also available for the western North Pacific basin, and similar parameters could be explored for a multitude of seasons and storms.

APPENDIX. DET/EMN/OFC COMPARISONS

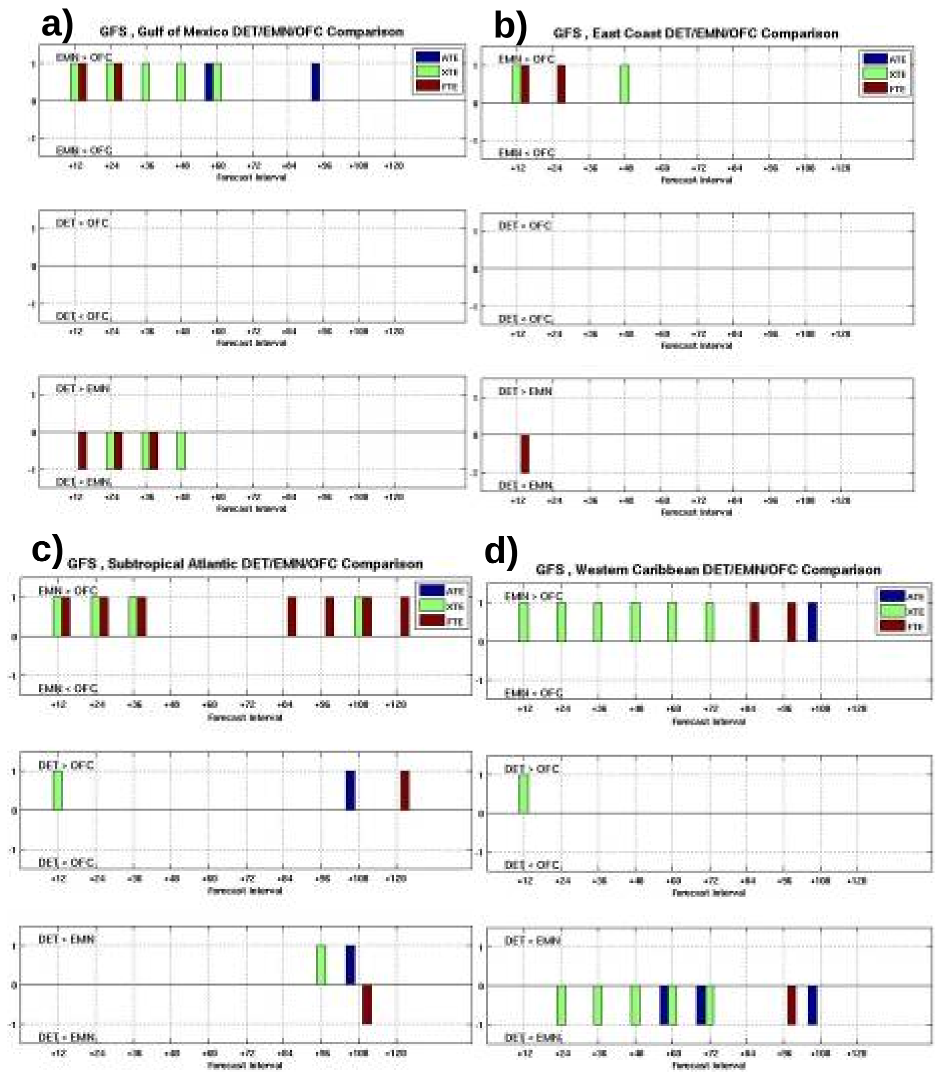


Figure 27. Statistically significant (at a level of 0.05) differences in ATE, XTE, and FTE (see designations on the right side of the top panel) for the GFS in (a) Gulf of Mexico and (b) east coast, (c) subtropical Atlantic, (d) western Caribbean, and (e) eastern Caribbean. EMN and OFC errors (top), DET and OFC (middle), and DET and EMN (bottom) are given as a function of forecast interval (h). The positive (negative) bar values identify statistically significant differences as defined by the labels in each panel.

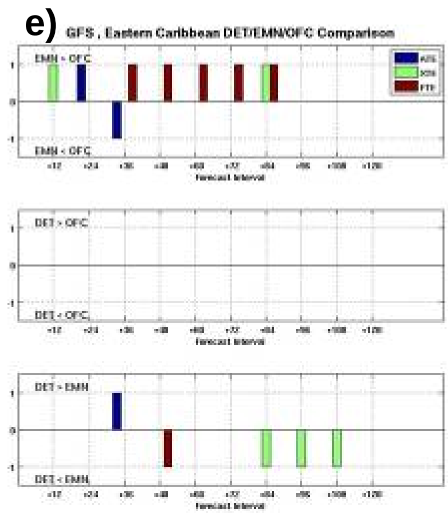


Figure 27 Continued. Statistically significant (at a level of 0.05) differences in ATE, XTE, and FTE (see designations on the right side of the top panel) for the GFS in the (e) eastern Caribbean. EMN and OFC errors (top), DET and OFC (middle), and DET and EMN (bottom) are given as a function of forecast interval (h). The positive (negative) bar values identify statistically significant (not significant) differences as defined by the labels in each panel.

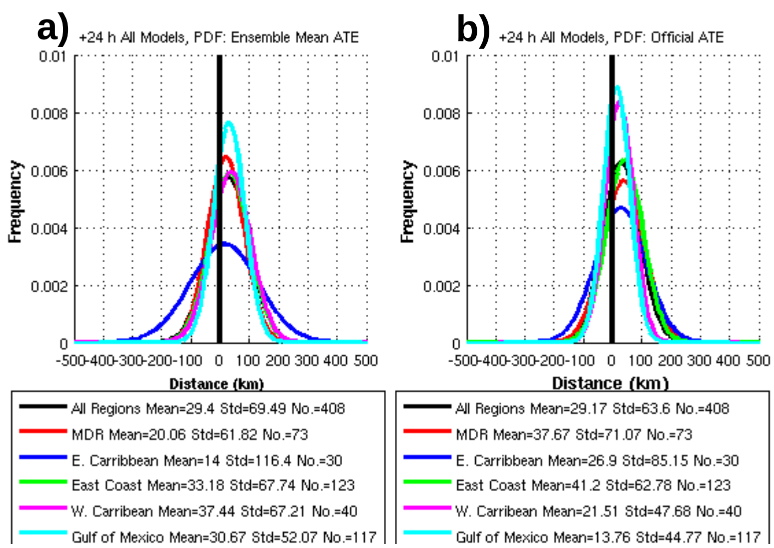


Figure 28. Normal probability distribution functions for the 24-h forecast ATEs by the (a) EMN and (b) OFC for the group of All Models. The abscissa is the positive or negative ATEs in kilometers, and the ordinate represents frequency of occurrence. Curves are color-coded by region (see box) with the mean, standard deviation, and number of members shown in the legend.

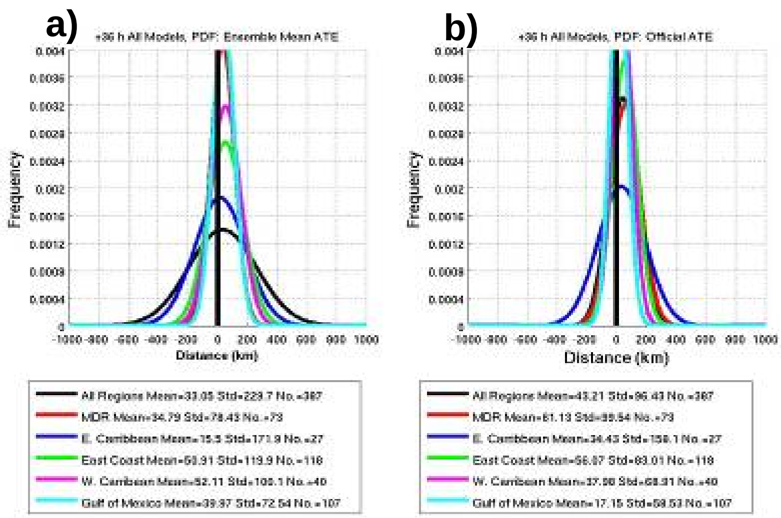


Figure 29. Normal probability distribution functions for the 36-h forecast ATEs by the (a) EMN and (b) OFC for the group of All Models. The abscissa is the positive or negative ATEs in kilometers, and the ordinate represents frequency of occurrence. Curves are color-coded by region (see box) with the mean, standard deviation, and number of members shown in the legend.

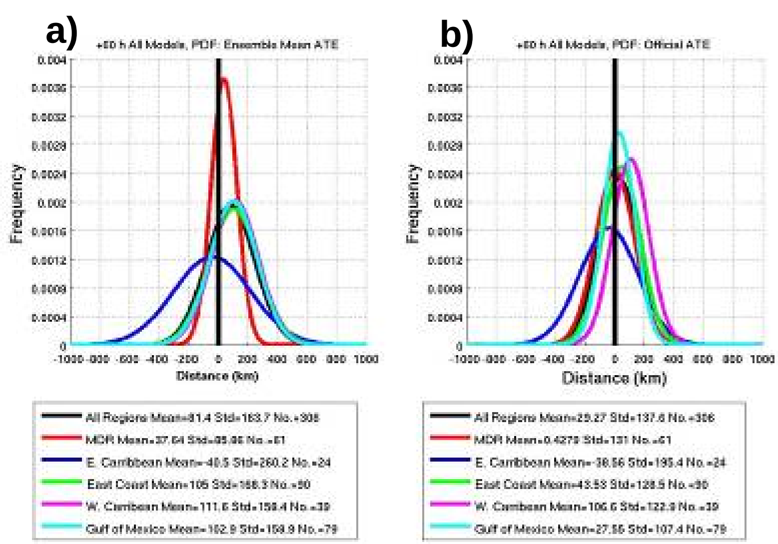


Figure 30. Normal probability distribution functions for the 60-h forecast ATEs by the (a) EMN and (b) OFC for the group of All Models. The abscissa is the positive or negative ATEs in kilometers, and the ordinate represents frequency of occurrence. Curves are color-coded by region (see box) with the mean, standard deviation, and number of members shown in the legend.

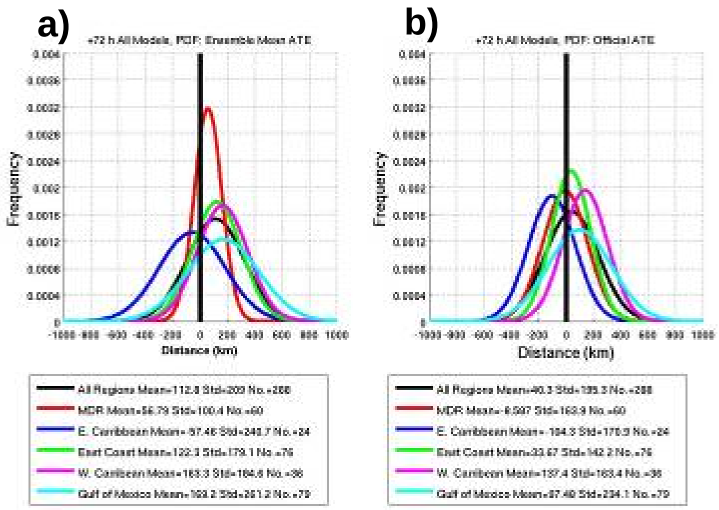


Figure 31. Normal probability distribution functions for the 72-h forecast ATEs by the (a) EMN and (b) OFC for the group of All Models. The abscissa is the positive or negative ATEs in kilometers, and the ordinate represents frequency of occurrence. Curves are color-coded by region (see box) with the mean, standard deviation, and number of members shown in the legend.

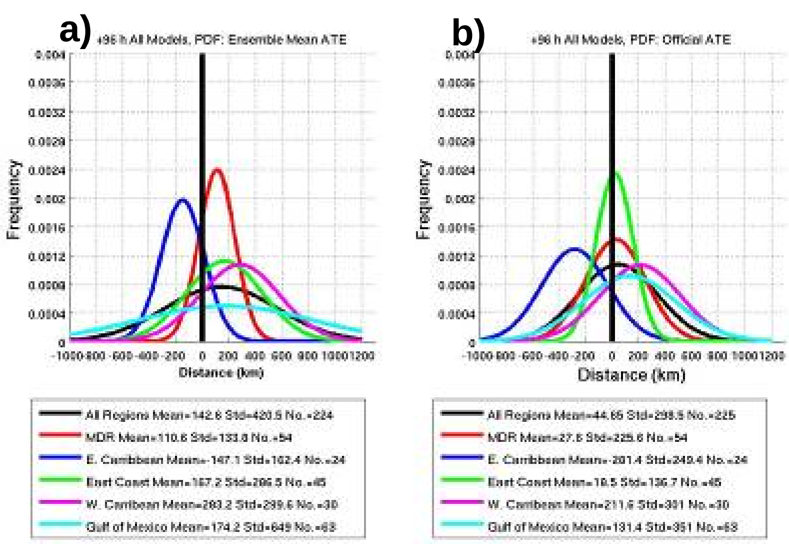


Figure 32. Normal probability distribution functions for the 96-h forecast ATEs by the (a) EMN and (b) OFC for the group of All Models. The abscissa is the positive or negative ATEs in kilometers, and the ordinate represents frequency of occurrence. Curves are color-coded by region (see box) with the mean, standard deviation, and number of members shown in the legend.

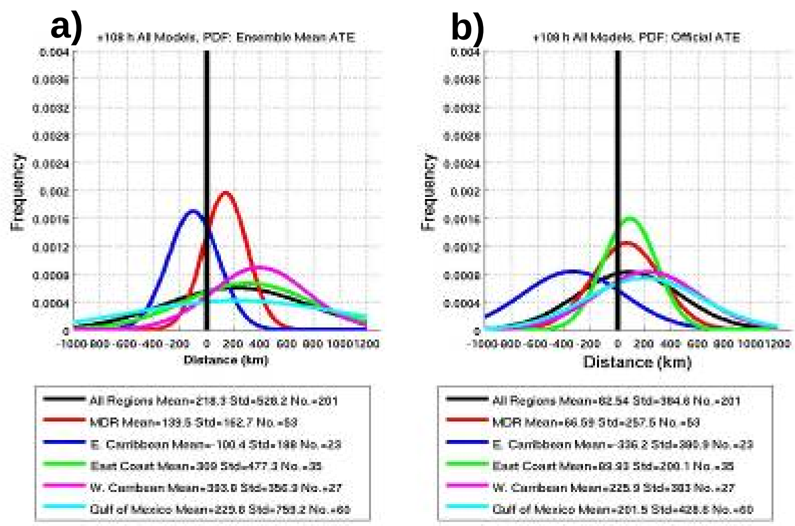


Figure 33. Normal probability distribution functions for the 108-h forecast ATEs by the (a) EMN and (b) OFC for the group of All Models. The abscissa is the positive or negative ATEs in kilometers, and the ordinate represents frequency of occurrence. Curves are color-coded by region (see box) with the mean, standard deviation, and number of members shown in the legend.

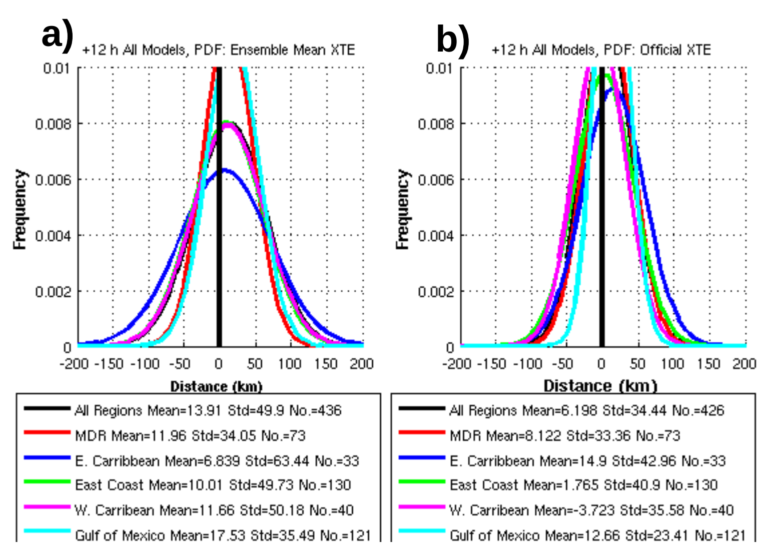


Figure 34. Normal probability distribution functions for the 12-h forecast XTEs by the (a) EMN and (b) OFC for the group of All Models. The abscissa is the positive or negative XTEs in kilometers, and the ordinate represents frequency of occurrence. Curves are color-coded by region (see box) with the mean, standard deviation, and number of members shown in the legend.

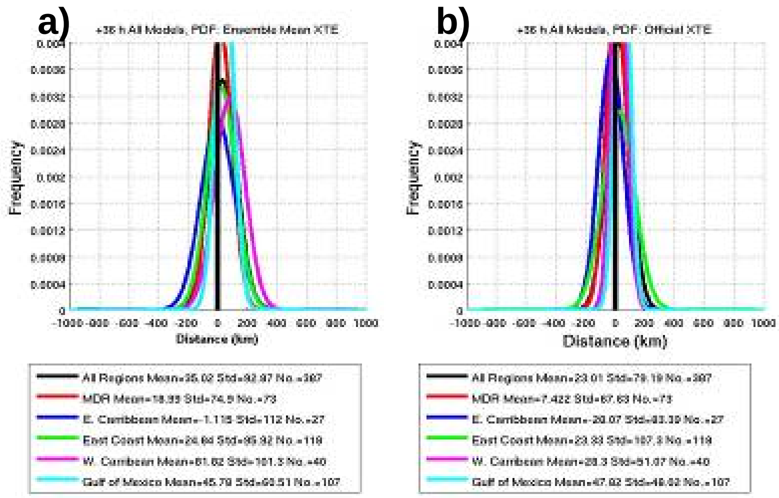


Figure 35. Normal probability distribution functions for the 36-h forecast XTEs by the (a) EMN and (b) OFC for the group of All Models. The abscissa is the positive or negative XTEs in kilometers, and the ordinate represents frequency of occurrence. Curves are color-coded by region (see box) with the mean, standard deviation, and number of members shown in the legend.

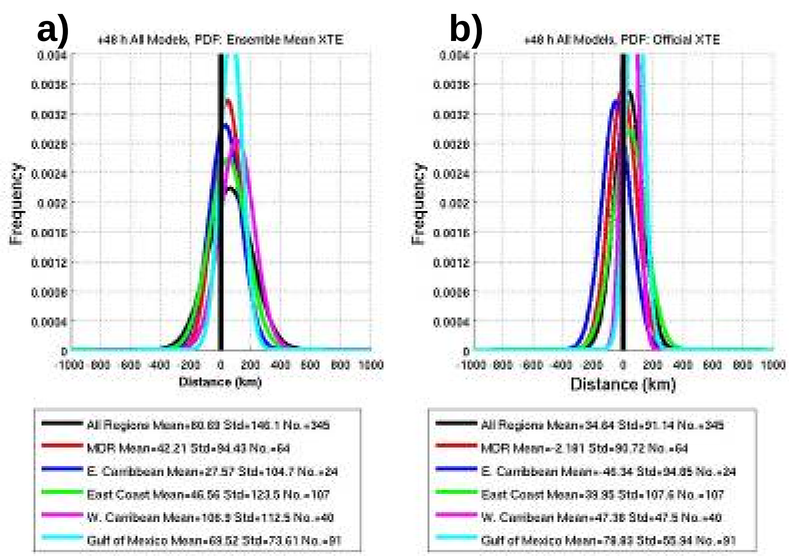


Figure 36. Normal probability distribution functions for the 48-h forecast XTEs by the (a) EMN and (b) OFC for the group of All Models. The abscissa is the positive or negative XTEs in kilometers, and the ordinate represents frequency of occurrence. Curves are color-coded by region (see box) with the mean, standard deviation, and number of members shown in the legend.

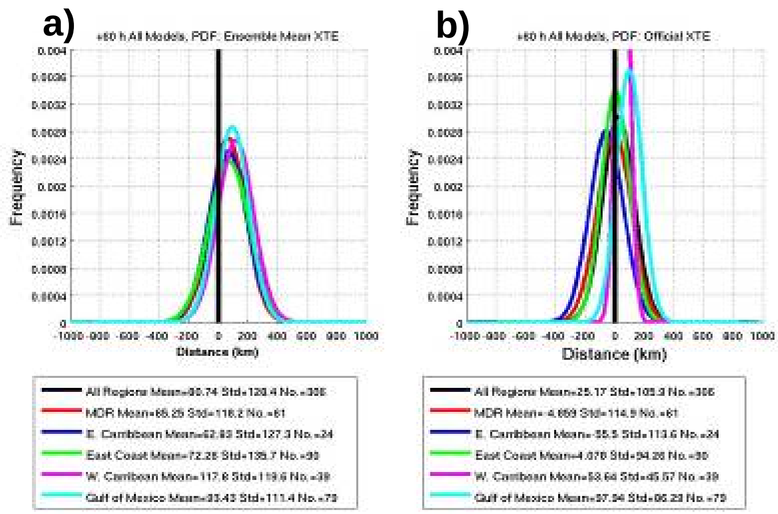


Figure 37. Normal probability distribution functions for the 60-h forecast XTEs by the (a) EMN and (b) OFC for the group of All Models. The abscissa is the positive or negative XTEs in kilometers, and the ordinate represents frequency of occurrence. Curves are color-coded by region (see box) with the mean, standard deviation, and number of members shown in the legend.

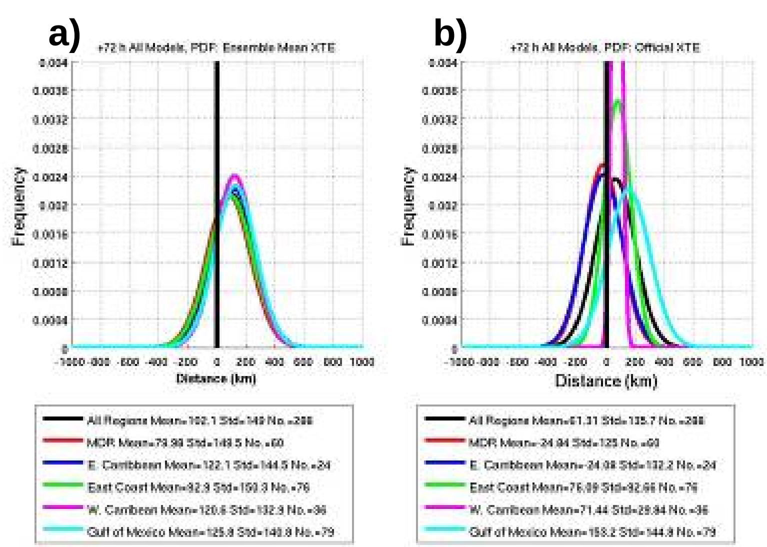


Figure 38. Normal probability distribution functions for the 72-h forecast XTEs by the (a) EMN and (b) OFC for the group of All Models. The abscissa is the positive or negative XTEs in kilometers, and the ordinate represents frequency of occurrence. Curves are color-coded by region (see box) with the mean, standard deviation, and number of members shown in the legend.

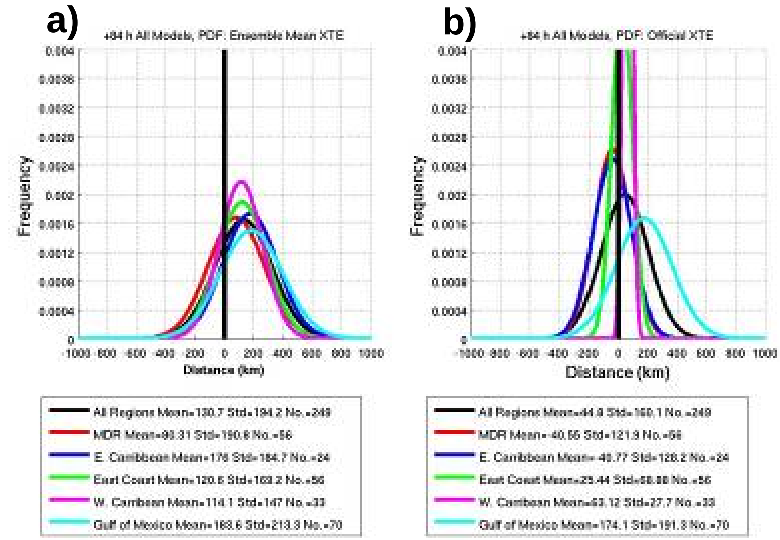


Figure 39. Normal probability distribution functions for the 84-h forecast XTEs by the (a) EMN and (b) OFC for the group of All Models. The abscissa is the positive or negative XTEs in kilometers, and the ordinate represents frequency of occurrence. Curves are color-coded by region (see box) with the mean, standard deviation, and number of members shown in the legend.

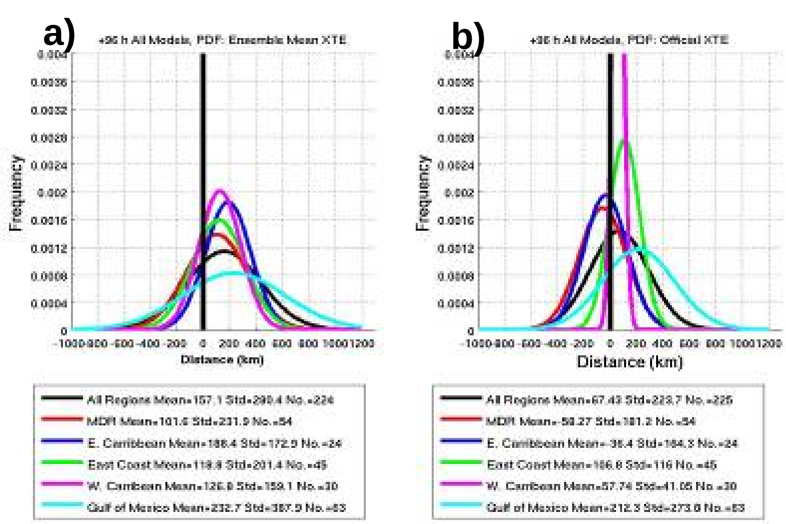


Figure 40. Normal probability distribution functions for the 96-h forecast XTEs by the (a) EMN and (b) OFC for the group of All Models. The abscissa is the positive or negative XTEs in kilometers, and the ordinate represents frequency of occurrence. Curves are color-coded by region (see box) with the mean, standard deviation, and number of members shown in the legend.

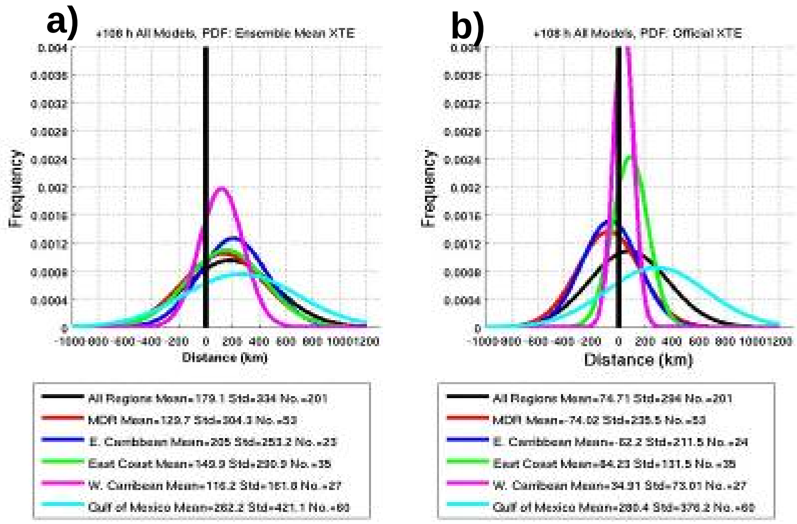


Figure 41. Normal probability distribution functions for the 108-h forecast XTEs by the (a) EMN and (b) OFC for the group of All Models. The abscissa is the positive or negative XTEs in kilometers, and the ordinate represents frequency of occurrence. Curves are color-coded by region (see box) with the mean, standard deviation, and number of members shown in the legend.

THIS PAGE INTENTIONALLY LEFT BLANK

LIST OF REFERENCES

Astroprof, 2010: A Shuttle Hangar? [Available online at: http://astroprofspage.com/archives/790] accessed 13 September 2010.

DeMaria, M., J. A. Knaff, R. Knabb, C. Lauer, C. R. Sampson, and R. T. DeMaria, 2009a: A new method for estimating tropical cyclone wind speed probabilities. *Weather and Forecasting*, **24**, 1573–1591.

———, S. Kidder, B. Sampson, J. Knaff, C. Lauer, and C. Sisko, 2009b: An improved wind probability program: A year 2 Joint Hurricane Testbed project update. 61st interdepartmental Hurricane Conference, Savannah, GA. [Available at http://www.ofcm.gov/ihc_09/linking_file_ihc09.htm.

Goerss, J S., 2000: Tropical cyclone track forecasts using an ensemble of dynamical models. *Mon. Wea. Rev*., **128**, 1187–1193.

———, 2007: Prediction of consensus tropical cyclone track forecast error. *Mon. Wea. Rev.*, **135**, 1985–1994.

Hauke, M.D., 2006: Evaluating Atlantic tropical cyclone track error distributions based on forecast confidence. M. S. Thesis, Naval Postgraduate School, 85 pp. [Available from http://handle.dtic.mil/100.2/ADA452140]

Majumdar, S. J., and P. M. Finocchio, 2009: On the ability of global ensemble prediction systems to predict tropical cyclone track probabilities. *Weather and Forecasting*, **25**, 659–680.

National Ocean Service (NOS), cited 2010: Ocean facts. [Available online at http://oceanservice.noaa.gov/facts/population.html] accessed 22 July 2010.

Netmba, cited 2010: [Available online at: http://www.netmba.com/statistics/histogram/].

NHC, cited 2010a: Tropical Weather Summary. [Available online at http://www.nhc.noaa.gov/archive/2007/tws/MIATWSAT_nov.shtml] accessed 21 July 2010.

NHC, cited 2010b: Tropical Weather Summary. [Available online at http://www.nhc.noaa.gov/archive/2008/tws/MIATWSAT_nov.shtml] accessed 21 July 2010.

NHC, cited 2010c: Tropical Weather Summary. [Available online at http://www.nhc.noaa.gov/archive/2009/tws/MIATWSAT_nov.shtml] accessed 21 July 2010.

NHC, cited 2010d: 2007 Atlantic Hurricane Season. [Available online at http://www.nhc.noaa.gov/tracks/2007atl.jpg] accessed 21 July 2010.

NHC, cited 2010e: 2008 Atlantic Hurricane Season. [Available online at http://www.nhc.noaa.gov/tracks/2008atl.jpg] accessed 21 July 2010.

NHC, cited 2010f: 2009 Atlantic Hurricane Season. [Available online at http://www.nhc.noaa.gov/tracks/2009atl.jpg] accessed 21 July 2010.

NHC, cited 2010g: Ike Graphics Archive [Available online at http://www.nhc.noaa.gov/archive/2008/graphics/al09/loop_5W.shtml] accessed 5 August 2010.

NHC, cited 2010h: [Available online at http://www.nhc.noaa.gov/archive/2008/graphics/al09/loop_PROB64.shtml.] accessed 5 August 2010

NHC, cited 2010i: [Available online at http://www.nhc.noaa.gov/archive/2008/graphics/al09/loop_PROB34.shtml] accessed 5 August 2010.

NHC, cited 2010j: [Available online at http://www.nhc.noaa.gov/archive/2008/graphics/al09/loop_T.shtml] accessed 5 August 2010.

NHC, cited 2010k: [Available online at http://www.nhc.noaa.gov/pdf/TCR-AL092008_Ike_3May10.pdf] accessed 5 August 2010

NHC, cited 2010l: [Available online at http://www.nhc.noaa.gov/aboutnhcprobs2.shtml] accessed 5 August 2010

NHC, cited 2010m: [Available online at http://www.nhc.noaa.gov/archive/2008/al09/al092008.wndprb.042.shtml] accessed 5 August 2010

NHC, cited 2010n: [Available online at http://www.nhc.noaa.gov/refresh/graphics_at1+shtml/024615.shtml?5-daynl#contents] accessed 13 September 2010

NHC, cited 2010o: [Available online at http://www.nhc.noaa.gov/aboutnhcprobs.shtml] accessed 17 September 2010

Shafer, J. A., 2006: A verification of the National Hurricane Center's tropical cyclone wind speed probability forecast product. M. S. Thesis, Department of Marine and Environmental Systems, Florida Institute of Technology, 90 pp.

Splitt, M. E., J. A. Shafer, S. M. Lazarus, and W. P. Roeder, 2009: Evaluation of the National Hurricane Center's tropical cyclone wind speed probability forecast product. *Weather and Forecasting*, **25**, 511–525.

Tsui, T., and R. Miller, 1988: Evaluation of western North Pacific tropical cyclone objective forecast aids. *Weather and Forecasting*. **3**, 76–85.

Wadsworth, cited 2010 [Available at http://www.wadsworth.com/psychology_d/templates/student_resources/workshops/stat_workshp/ttest_betwn/ttest_betwn_02.html.] accessed 2 August 2010.

Wilson, S. G., and T. R. Fischetti, 2010: Coastline population trends in the United States 1960–2008. [Available online at http://www.census.gov/prod/2010pubs/p25-1139.pdf] accessed 23 July 2010.

Wilks, D. S., 2006: *Statistical Methods in the Atmospheric Science*, 2nd edition. Elsevier Academic Press, 627 pp.

Winters, K. A., 2006: Providing tropical cyclone weather support to space launch operations. *Extended Abstract 9A.5, 27th Conf. on Hurricanes and Tropical Meteorology*, Monterey, CA, Amer. Meteor. Soc. 9A.5.

THIS PAGE INTENTIONALLY LEFT BLANK

INITIAL DISTRIBUTION LIST

1. Defense Technical Information Center
   Ft. Belvoir, Virginia

2. Dudley Knox Library
   Naval Postgraduate School
   Monterey, California

3. Air Force Weather Technical Library
   Asheville, North Carolina

4. Professor Patrick Harr
   Naval Postgraduate School
   Monterey, California

5. Professor Russell Elsberry
   Naval Postgraduate School
   Monterey, California

6. Mr. William Roeder
   45 Weather Squadron
   Patrick Air Force Base, Florida

7. Captain Jay Neese
   17 Operational Weather Squadron
   Hickam Air Force Base, Hawaii